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ELECTRON BEAM RECORDER APPLICATIONS STUDY.(U)

AUG 77 J J GREED, G N WALLMARK DAAK70-77-C-0111

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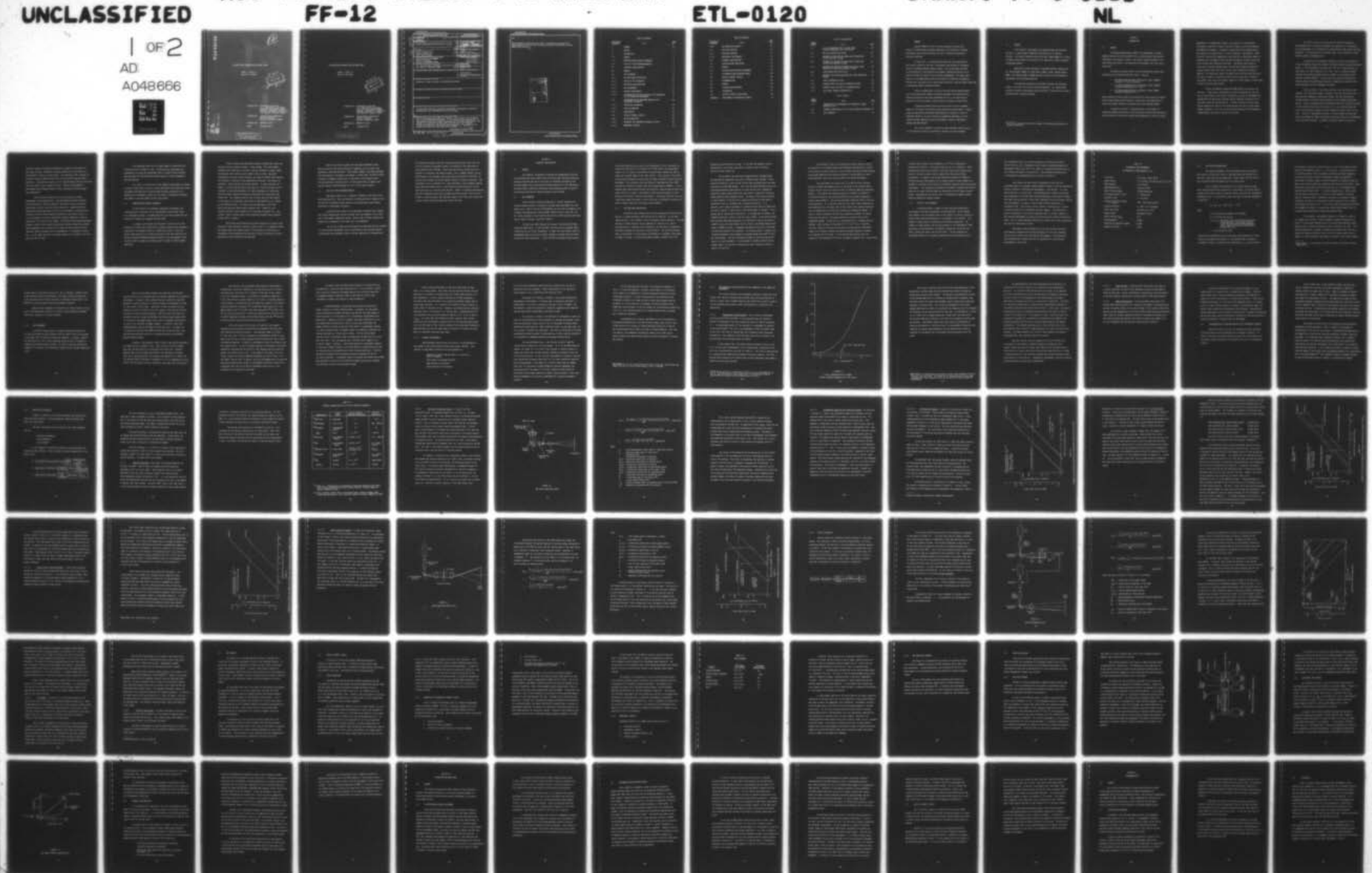

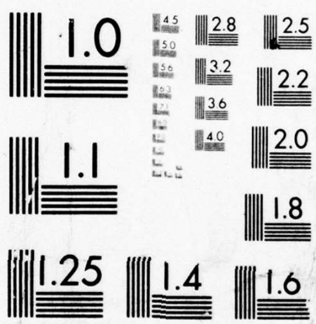

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ELECTRON BEAM RECORDER APPLICATIONS STUDY

James J. Greed, Jr.
Gerald N. Wallmark

Prepared For: Department of the Army
U. S. Army Mobility Equipment
Research & Development Command
Engineer Topographic Laboratories
Fort Belvoir, Virginia 22060

Prepared By: Carson Alexiou Corporation
345 Wilson Avenue
Norwalk, Connecticut 06854

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Electron Beam Recording (EBR) was studied in the context of its potential uses in the Defense Mapping Agency. It was found to have applications in cartographic recording, textual recording, and microfiche preparation. The making of pressplates from EBR masters involves the use of optical projection systems and "projection speed" materials. The properties of several such materials were found to be suitable. → next page

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Non-cartographic users were also found, including the potential for exploitation of the very high resolution available from an EBR for mass memory applications.

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i. Summary

Contract DAAK70-77-C-0111 has been conducted to assess the utility of electron beam recording technology in the context of automated cartographic and textual publishing, and as an information storage and retrieval technique.

In many areas, the technology has been seen to be applicable to the current increase in the level of automation and increase in throughput rates at the Defense Mapping Agency Centers. For electron beam recorders to be considered in the production environment, maximum resolutions of the order of 10,000 to 16,000 TV lines have been recommended. This means that a majority of the DMA-produced charts can be made via projection platemaking, but that full size (48" by 72") charts must be made by a step and repeat imposition of projection images from EBR microforms.

Serious consideration of the use of 35 mm electron beam recorders and existing publishing industry peripheral equipment for projection platemaking and pagination have been recommended for use in the publishing of textual and text with graphic products which are produced in book format.

Projection platemaking with existing state of the art equipment appears to be feasible from electron beam recorder microform output. Further study and quantitative performance measurements are required in order to determine whether or not such projection platemaking techniques can truly satisfy the most demanding accuracy and geometric fidelity requirements imposed upon DMA products.

The issue of geometric accuracy has been addressed, and the use of a 2 mil absolute accuracy and separation congruency has been proposed.

ii Preface

This technical investigation was conducted under the direction of the U. S. Army Engineer Topographic Laboratories at Ft. Belvoir, Virginia. The project technical monitor was Capt. Ronald Magee (U. S. Army) of USAETL working under the direction of Mr. Howard Carr, Chief, Automated Cartrography Branch.

Responsible liaison personnel at the DMA Production Centers were Mr. Fred Hufnagel, DMAAC, Mr. Bruce Opitz, DMAHC, and Mr. George Stewart, DMATC. Mr. Robert Penney of DMAHQ provided liaison with the Headquarters perceptions of the program objectives.

The study was conducted at the Electron Systems and Technology Center, a division of the Carson Alexiou Corporation. Mr. James Greed* served as principal investigator and was assisted in the work by Mr. Gerald Wallmark and Mr. Douglas Willumsen.

*Mr. Greed is now with the Electron Systems and Technology Corporation of Norwalk, Connecticut.

SECTION I

INTRODUCTION

1.0 GENERAL

The Defense Mapping Agency (DMA) is the Department of Defense component charged with the responsibility to provide current and accurate information to navigators, planners, and logistic analysts working in the three operational spaces: the aeronautical environment, over land, and in ocean space.

The DMA has organized itself into three production centers which concentrate on the three navigational spaces. They are:

1. The Defense Mapping Agency Aeronautical Center (DMAAC), located in St. Louis, Missouri,
2. The Defense Mapping Agency Hydrographic Center (DMAHC), located in Washington, D. C., and
3. The Defense Mapping Agency Topographic Center (DMATC), located in Washington, D. C.

These production centers produce an extraordinarily wide variety of products which include complex charts and maps, textual data, and combinations of textual and graphic materials intermixed within one document product.

In general, the work is characterized by a large amount of repetitive updating and editing. Much of the work involves the correction of existing charts to reflect the latest known information in terms of surveys,

geographical or topographical changes, and especially in the aerospace environment, operational changes relating to airways, and aircraft approach and departure procedures. The amount of work that must be accomplished by each center, on an annual basis, is truly voluminous. The editorial nature of much of the work has suggested for some time that a substantial amount of automation can be brought to bear upon the cartographic process through the use of digital data processing techniques. The DMA has been working in this area for the past fifteen years, and has made substantial progress in creating digital data files from its very large storehouse of graphical material. As time passes, many of the DMA's users find that they have great utility for products in the form of digital data records and, in some of the centers' work, the use of graphic output as a final product is diminishing in favor of digital data records.

Primary requirements imposed upon DMA products are accuracy and fidelity. In many cases, the products are used by navigators who rely not only on the accuracy of the textual information, but also on the geometrical juxtaposition of land masses and other terrain features to guide an air or sea vessel safely to its destination. In times of conflict on land, topographic products are used for fire direction and like uses in close combat support situations. So it can be seen that the accuracy of the information on DMA products can truly be called life critical.

The critical nature of the work,and the liability accepted by the Government and its analysts who prepare this material, are responsible for the development of a requirement for extraordinarily high quality proofing operations. The importance of the proofing steps in the production of these products cannot be overemphasized.

In addition to the procedural problem of proofing, the automation of the cartographic process must address the human reaction to machine-produced graphics. The cartographic and graphic arts are rich in tradition and, to some extent, are unto themselves an art form. Thus, it appears extremely important that machine-produced graphics resemble, to the greatest extent possible, man-made products. In many cases, the artifacts of mechanical scanning render such machine-made products as immediately discernible from those created by skilled cartographic draftsmen.

With the advent of very high resolution laser and electron beam scanners, this problem has begun to diminish. Over the past decade, the U. S. Army Engineer Topographic Laboratories (USAETL) has been investigating the applications of electron beam technology to the automated cartographic process. With an extremely mature entertainment television industry available in this country and the rest of the world, it is not surprising that the use of high resolution cathode ray tubes formed the original basis for this work. A series of developmental devices, in which cathode ray tubes were used as printheads to impose cartographic and textual material on photographic film, have been developed. In general, available cathode ray tubes are

limited in graphic arts quality performance to formats of the order of a few inches and total information recording capabilities on the order of a few thousand TV lines per raster height. This technique, then, requires an extremely accurate flatbed plotter which can do multiple step-and-repeat operations. The mechanical aspects of this step-and-repeat operation obviously limit the speed of such a graphic terminal. Beyond the development of cartographic CRT printhead plotters, direct recording with electron beams was investigated.

Direct electron recording on film has proven to be highly advantageous in many applications. The photographic emulsions available are extraordinarily fine grain material, and require a very low electron beam dosage to develop very high optical densities. Coupled with these photographic medium advantages, has been the development of extremely high resolution electron optics permitting selection of spot sizes as small as 1 to 5 micrometers, and total information recording capability of tens of thousands of TV lines per raster height. Following an exploratory development program in which a 70 mm format electron beam recorder successfully produced both cartographic data and imposition of names and other textual data and symbology, USAETL proceeded with the development of a cartographic electron beam recorder (EBR), which has a recording format of 5 x 8 inches (5-1/2 inch wide roll film is used).

The cartographic EBR, built by Image Graphics Incorporated, was delivered to ETL in October of 1976. As more and more experiments were conducted at ETL using the cartographic EBR as a graphic output terminal, many new ideas for EBR applications beyond those of strictly topographic plotting surfaced.

As a result, in the Spring of 1977, DMAHQ directed USAETL to conduct a contract study effort to assess, in both qualitative and quantitative terms, the general applicability of electron beam recording technology to the generation of cartographic products in this sphere of automated cartography. This report is the work product of that study effort.

1.1 COMPUTER-DRIVEN GRAPHIC RECORDING

In the context of an automated cartographic environment, the recording effort is basically one of transforming a digital data record to a cartographic product. As emphasized above, this must be done with the provision of several very adequate proofing steps.

In general, this digital data record will reflect the one time conversion via some form of scanning of a graphic record and the subsequent conversion of the graphic record to a digital data record. Often, this digital data record will be called and portions of the data record will be edited as updated information becomes available to the cartographer. After the data record is updated, the edited record is ready for output graphic generation.

There are many known techniques by which a digital data record can be used to drive a graphic recorder. These include: full scale graphic plotters using either pens or scribers, optical recorders of either flatbed or drum-type, and a smaller scale recorder such as an EBR. One other technological variable further delineates the types of graphic data terminals. This variable is involved in the methodology of plotting. Two methods are available: raster plotting and vector plotting. In raster plotting, the graphic is called from the digital data base on a line-by-line basis, and is "painted" on the recording medium in a fashion analogous to a television picture (normally without the interlace associated with conventional home television). This technique implies that no matter what the data density of the graphic to be produced, every point on that graphic will be scanned by the recording system. The vector plotting technique, on the other hand, plots data only where graphic features exist. Generally, this requires relatively rapid movement of the recording instrument (i.e., pen, scriber, light or electron beam) along serpentine features and/or character strokes within a graphic.

While many plotting machines have been designed to do either raster plotting or vector plotting, the EBR is unique in that it is adaptable without any changes other than command signals to do plotting in either mode as a consequence of the tremendous ease with which virtually inertialess electron beams may be rapidly deflected and modulated.

Many of the plotting systems that have been developed to date employ relatively high inertia mechanical components and are rather time consuming in plotting operations. Some systems, however, have been developed which can operate at reasonably high speeds; in these cases, the data transfer available in computer hardware and, in particular, direct memory access circuits become the limiting factor. At the present time, it appears that the utilization of EBR technology will fall in the latter category.

1.2 UTILITY OF EBR MICROFORM GRAPHICS

EBR output graphics are, in general, produced on fine grain silver halide emulsion film. They are available in either positive or negative form, and the positive/negative phase change may be accomplished either through electronic or photographic processes.

An EBR microform graphic can be generated in seconds from a digital data record assuming that the data transfer rates are adequate in the "front end" of the graphic composition system. Vector lines of widely varying line weights can be generated as can names, data, and symbology.

The utility of these microform graphics includes applications relating to direct product development such as transformation from microform graphics to pressplates and subsequent product printing, generation of transparencies

for projection displays, and other interesting applications that, while not strictly producing cartographic output, are potentially very applicable to other problems within the DMA. These other applications include the use of the EBR as a continuous tone image recorder, such as LANDSAT imagery, and the exploitation of the extremely high packing density available in the EBR as an archival data recorder for either graphic (analog) or digital recordings. EBR technology is also a contender for a high performance, high throughput Computer Output Microform (COM) terminal. Both microfilm and microfiche can be produced with ease by an electron beam recorder. USAETL is currently experimenting with the cartographic EBR using a standard microfiche format in which one set of DAC's is used to address the individual pages of the fiche, and a second set is used to position the recording spot within the page.

SECTION II

TECHNICAL INVESTIGATION

2.0 GENERAL

The technical investigation conducted has encompassed an analysis of the present and future capabilities of electron beam recording technology, processes available now and in the future for producing pressplates from microform images, the current and anticipated product mix of the DMA centers, and those areas in which the attributes of EBR technology might be applied for ancillary uses such as image and digital data recording.

2.1 EBR TECHNOLOGY

Direct electron recording technology as a useful technique for creating image and graphic information, has been under development for some twenty years. Much of the early developmental work was done at companies such as Ampex, CBS Laboratories, Eastman Kodak, General Electric, IBM, RCA, and 3M. Public awareness of the viability and utility of EBR recording technology came to light in several "space age" programs.

In both cases, NASA programs led the way in exploiting EBR image recording capabilities. In the mid-1960's two very exciting programs demonstrated the utility of this technology. In 1966, the Lunar Orbiter satellite photographed areas of the lunar surface intended as landing sites for Apollo missions of lunar exploration. In this satellite and ground station system,

an electron beam device was used to scan photographic film in the satellite, convert the variations in film density to a video signal, and subsequently transmit it to a ground station where an electron beam recorder was used to create the recorded images of the lunar surface. Also starting in the 1960's and continuing through the present time, has been a program of earth resources assessment. This started as the Earth Resource Technology Satellite (ERTS) Program and continues at present under the program known as LANDSAT. In this program, which enjoys multi-national participation, electron beam recorders are used in the U.S.A., Brazil, and Canada to record satellite images of large portions of the earth's terrain and seascapes. The devices that are in use to record these images have been in service for years, and generally operate on a heavily loaded, three-shift seven-days-a-week schedule.

2.1.1 EBR FUNCTIONAL DESCRIPTION

An electron beam recorder may be easily understood by starting from the basis of home television with which we are all familiar. In our home television sets, a hot cathode is used to stimulate electron emission. Electron emission is drawn from this source, modulated in intensity by a control grid upon which is impressed video information, and the beam is subsequently deflected (scanned) and focussed by electron optics. The resulting electron beam is accelerated to a high energy, and impinges on a phosphor screen where an image is created. In the electron beam recorder, virtually all of the

processes are qualitatively the same. In the EBR, the phosphor screen is replaced with a film plane, upon which is placed a piece of electron sensitive silver halide film.

At this point, the qualitative comparisons are straightforward. The quantitative comparisons are quite a different story, however. Direct electron recording on silver halide film has many advantages which have been exploited in current EBR designs. First, the very high efficiency with which high energy electrons expose grains of silver halide allow a substantial reduction in beam current density over that which is required to stimulate photon emission from a phosphor screen. The impact of this high efficiency is seen primarily in the ability to create extraordinarily high specific resolutions (that is, extremely small electron beam spots). It is possible, and in general desirable, to produce electron optics in EBRs which are vastly superior to those found in the entertainment TV industry. This is another way of stating device resolution. In the American TV industry, the standard resolution is 525 TV lines per raster height. In the early electron beam recorders mentioned previously, the resolution is more of the order of 10,000 TV lines per raster height (such as found in the Goddard Space Flight Center's LANDSAT recorder). Subsequent developments have led to the design of 20,000 and 30,000 TV line recorders. As discussed below, it appears that ultimate performance limits probably lie between 30,000 and 50,000 TV lines per raster height. The total information content of such high resolution rasters is truly formidable. If one considers a 50,000 by 50,000 picture element raster in a two-level recording, the total information content is some 2.5 billion bits.

The desirable virtues of recording with electron beams do require the imposition of instrument design and performance characteristics related to the nature of electron emission. These include high quality vacuum systems, precise beam addressing and focusing electronics, and the ability to move electromechanical parts with precision within the vacuum environment.

The requirements for vacuum level in an EBR are quite variable. The most stringent requirements occur in the region of the electron source. Electron sources typical of those utilized in an EBR are generally thermionic emitters. (This means that electron emission is produced in proportion to the work function of the electron emitter and its elevated temperature normally around 2600°K.) Two failure mechanisms attend this type of electron source operation. It is desirable that the first order failure mechanism be the predominant one; this means that failure should occur through evaporative loss of cathode material rather than through ionic bombardment damage. In order to enjoy the maximum lifetime from a thermionic cathode, the vacuum levels must be kept at a low enough pressure to preclude serious ionic bombardment damage. In the case of a non-activated (i.e., tungsten emitter) cathode, a total pressure of the order of 10^{-7} to 10^{-8} torr is required. From this region of relatively high vacuum (low pressure), the requirements become less stringent although the pumping throughput generally increases as we approach the film plane. In the electron beam landing area, the presence of the photographic film with its organic components and, in particular,

its water vapor content, the achievement of a 10^{-8} torr vacuum while theoretically possible, is not highly practical nor is it necessary. These considerations lead to the designer's conclusion that a multi-stage vacuum system is the most practical way to approach the satisfying of these requirements. In general, the vacuum conductances between the regions of different pressure requirements and the pumping speeds to these chambers are designed in accordance with relatively predictable outgassing loads and pressure requirements. The very mature technologies of mechanical roughing and foreline pumps and oil vapor diffusion pumps are appropriate for this type of vacuum system. Consideration can also be given to turbomolecular pumping systems backed by mechanical roughing systems.

2.1.2 STATUS OF THE TECHNOLOGY

As discussed above, a number of high technology organizations participated in the early development of EBR technology. At the present time, however, only one company known to the authors is directly involved in electron beam recording technology as a key element of its business. This company is Image Graphics Incorporated of Fairfield, Connecticut. The founders of Image Graphics were the key personnel in the development of EBR technology at CBS Laboratories in Stamford, Connecticut, during the late 1950's, through the 1960's and into the 1970's. IGI has produced the cartographic EBR which is presently undergoing test and evaluation at ETL.

The cartographic EBR is not a device produced to the absolute ultimate state of the art, but is adequately close to what we understand theoretical performance limits to be, that it is useful as a comparative projection as to the ultimate performance of such devices. The performance characteristics of this machine as promulgated by IGI are given in Table 2-1.

Some concern has been voiced in Government circles that the technology may be on a somewhat tenuous footing if there is only one organization actively involved in the design and development of such devices. It is our belief that this is not the case. The microelectronics industry has spurred many developments of electron beam recording technology in the quest of higher and higher packing density in large scale integrated circuits and memory devices. These developments, in general, parallel many of those required for a cartographic EBR. They generally work at specific resolutions far in excess of those desirable for a cartographic machine, however. The difference in specific resolution is not terribly important; what is critical, however, is the continued development of the ability to position and control fine electron beams. This is being addressed exhaustively by several very large organizations here and also intensively in Japan.

The authors have concluded that in this age of lasers and solid state devices, advanced electron beam technology still has very important roles to play in many of our technological developments. We believe that the microelectronics industry may well be responsible for revolutionary developments in this field.

TABLE 2-1

CARTOGRAPHIC EBR PERFORMANCE

(AS PROPOSED BY IMAGE GRAPHICS, INC.)

Film Sizes	5-1/2 inch, 70 mm, 35 mm
Image Formats	5 x 8 inches, 65 x 86 mm, 24.6 x 37.3 mm
Beam Diameters	3 & 6 microns
Beam Addressability	32,768 x 32,768
Vector Plotting Speed	125,000 points/sec
Line Width Control (5 bit)	3 - 250 microns
Character Sizes	4 - 36 points
Character Generation Speeds 4 - 6 points	1360 - 225 characters/sec
Character Rotation	0 - 359° in 1° increments
Raster Scan Rates	Variable up to 2 KHz
Dynamic Range	64 shades of gray
Optical Density (D_{max})	2.3+
Video Bandwidth	10 MHz
Congruity of Sequential Images	0.003%
Geometric Fidelity	0.01%

2.1.3 EBR DESIGN CONSIDERATIONS

The present fundamental limits with which we are faced concern both specific resolution in terms of line edge acuity and the ability to maintain a given spot size and shape over a large format, and the issue of very fine positioning and addressing of an electron beam.

First, consider the performance of an electron optical column which focuses and positions a beam over a large format. As in most optical systems (light optics as well as electron optics), the spot size is generally optimized on-axis. In an electron column, the spot size may be represented as equation 1:

$$d_s = d_o + c_1\theta + c_2\theta^2 + c_3\theta^3 + \cdots c_n\theta^n \qquad (1)$$

where

d_s is the spot size anywhere in the format,

d_o is the spot size on-axis,

c_1, c_2, c_3, and higher order coefficients are derived from properties of the electron optical column including electron beam divergence angle, spherical aberration coefficients, and the like, and

θ is the deflection angle.

Faced with the knowledge that the on-axis spot, when deflected, will tend to grow in accordance with equation 1, the designer seeks to reduce to a minimum or to zero, if possible, the coefficients, c_1, c_2, and so forth.

He also seeks to design his electron optical column to have adequate length such that the deflection angle, θ, is not excessive. The design solution is generally twofold; first the geometric and field uniformity properties of the electron optical column are optimized to reduce the aberration coefficients, secondly, dynamic correction waveforms are applied to keep the beam in focus and corrected for astigmatism and coma across the format. These corrections can be highly effective particularly in an electromagnetically focussed and deflected system. It has been suggested by Dr. Albert Crewe[1] that the proper juxtaposition of a series of electromagnetic correction devices (including dipoles, quadrupoles, hexapoles, and octopules) properly controlled, can result in a high quality electron beam spot over a 50,000 spot diameter deflection field. If this can be done successfully, aberrations will probably be reduced to a second order effect and the capabilities for accurate beam positioning will become the dominant effect.

If we consider a cartographic product or an image of a scene to be a sequence of artificial "picture elements" (generally referred to as pixels), it would seem reasonable that our electron beam addressing system should be able to position the beam to within a fraction of a pixel. If an electron beam device is capable of producing satisfactory beam size over a 50,000 spot diameter deflection field, and if we further require that we address to within the modest requirement of one-half of one picture element,

[1] Crewe, Albert V., Enrico Fermi Institute, University of Chicago, Private Communication.

we then require a positional accuracy of 1 part in 100,000. Stated in terms of the deflection amplifier performance, this means a deflection amplifier signal-to-noise ratio of 100 dB, certainly a performance figure that is very difficult to achieve and most likely not measurable directly.

Added to these fundamental considerations are other practical issues such as film dimensional stability in a widely varying humidity environment (from in-air storage to in-vacuum recording).

2.1.4 EBR PERFORMANCE

As we have discussed above, it appears theoretically practical to consider maximum recording formats within one frame of data to be bounded at the upper limit by 50,000 by 50,000 spot diameters. In general, however, the application of a new or high technology system to what is ultimately a production environment usually requires, in terms of practical application, somewhat of a derating of the performance capability from ultimate theoretical limits.

Several electron beam recorders have been built over the past few years which can be considered practical machines adaptable to a production environment. In general, these machines have been specified to have 50% modulation transfer function at a spatial frequency corresponding to 10,000 TV lines across a 70 mm format. (Note that in order to achieve this performance in excess of 14,000 TV lines are scanned in the vertical direction to account for scan direction sampling.) EBRs with which the authors are personally familiar include the CBS Model 70c electron beam recorder which is installed at the Goddard Space Flight Center in Greenbelt, Maryland and is used for the recording of LANDSAT imagery. In addition, three 70 mm framing machines, known as CBS Model 70f,have been built. Of these, one is installed in the Brazilian LANDSAT station near Sao Paulo, Brazil, and two have been delivered in-plant to a program sponsored by the Advanced Research Projects Agency.

In general, these machines exhibit stable, high quality performance at frequencies up to 10,000 TV lines. They all have a 3 micron diameter beam spot, and the majority of the machines use SO-219 film. Recently, NASA has been utilizing Kodak Type SO-438 in the CBS Model 70c recorder which has a continuous motion film transport and appears not to suffer from the charging effects discussed in paragraph 2.1.6.1 as a consequence of using SO-438 film (which does not have a conductive layer under the film emulsion).

Most recently, the cartographic EBR produced by Image Graphics Incorporated of Fairfield, Connecticut, has been delivered to Ft. Belvoir. The machine was installed at ETL in October of 1976 and, as yet, remains to be final acceptance tested. This machine is designed to handle up to 5-1/2" wide film and to expose formats up to 5" by 8". A digital beam positioning system is included which has the capability inherent in the digital-to-analog converters to address 2^{15} (32,768) data points along an 8" line. (More recently, the 2^{15} bit DAC's have been replaced by 2^{18} bit DAC's; the 2^{15} bit units are now used for "coarse" positioning such as the start of an individual page when recording in microfiche format, with the 2^{18} bit DAC's serving to control the spot position within the page.)

During the course of this study, ETL supplied to the authors representative test patterns recorded by the cartographic EBR using internally generated calibration patterns. These patterns appear as a matrix of cross scan lines of spatial frequencies corresponding to 16,328 TV lines down to 256 TV lines, and were produced before the machine was fully "tuned" to optimum performance. In addition, sensitometric steps are included in the test pattern matrix. In the film otuput supplied to the authors, microscopic examination indicated that the 16,328 TV line frequency would be useful for graphic arts quality work on axis. On the edges of the format, and in the corners, graphic arts quality appeared achievable at 8,192 TV lines. It is the authors' opinion that, in general, with an electromagnetically focused and deflected electron optical column of the geometry and quality found in the cartographic EBR, that the 16,328 TVL performance seen on axis is also achievable at the extremes of the format.

In summary, while the advertised performance of 32,768 points was not observable in the film chips supplied by ETL, it is the authors' opinion that a practical production environment machine can be reliably specified at somewhere between 10,000 and 16,000 TV lines and will offer stable performance of graphic arts quality at these frequencies.

As mentioned above, the EBR beam position may be controlled in either a vector or a raster plotting format. In general, for the product scales and projection systems considered, the EBR spot size that appears to be most practical is of the order of 5 to 6 micrometers (approximately one-quarter mil). Generally, this will produce lines,after projection to a full size graphic,that are smaller by a factor of four than the minimum line weights normally utilized in even the finest detail in cartographic products. In a vector plotting mode, line weight control is produced by "wobbling" the electron beam spot as it draws vector strokes. This has the extremely desirable affect of plotting a wider line which has the edge acuity of a very much finer spot. Thus, the apparent spot intensity profile appears to be virtually "square". Normally, the average density of cartographic products is such that a product plotted in the vector mode will consume much less time for plotting than one accomplished by raster plotting techniques. Similarly, characters and symbols may be generated by vector techniques as well as by raster techniques. A substantial amount of software and hardware has already been developed to allow for the recording of graphic arts quality symbology and characters using the electron beam recorder.

Raster plotting techniques are obviously useful when the data base is in a raster format. Most often, this may take the form of pictorial data which is recorded as an analog image and in which tonal control is of great importance. In such a product application, the EBR technology is utilized in the field for which it was originally developed, namely that of analog image recording. It is possible with the EBR to control exposure to density units of the order of 0.01. Normally, the minimum density achievable (base plus fog) is of the order of 0.1 density units. Maximum densities of 3 are possible, but in practice normally a density of 2.1 to 2.4 is used as a D_{max}. It is thus seen that the EBR can offer a dynamic range limited primarily by the sensitometric characteristics of the recording medium which will be of the order of 200:1 (useful primarily for machine-read information). Human observers perceive the image ouput of the EBR in its analog recording mode as a completely continuous tone image.

2.1.5 ACCURACY REQUIREMENTS

EBR performance specification and analysis is straightforward in the context of the electro-optical display and recorder industry. This industry is accustomed to working with such parameters as:

- Modulation Transfer Function (MTF) as a function of spatial frequency
- Point and/or Line Spread Functions
- Edge Acutance (or gradient)
- Optical Density of Film Record

All of the above performance specifications are quantitative, and can be measured by precision equipment. Human interpretation is not required to assess whether or not a performance specification is met.

The graphic arts industry, although it uses certain quantitative measurements of performance, is far more open to subjective evaluation. A "good graphic" is one that is pleasing to the eye; it has "crispness", etc. The observer's subjective perception is generally regarded as more important than any photo-optical measurements that might be made.

This presents a dilemma in the DMA world of cartography in which the quest for the application of new technologies is directed by personnel allied with the engineering sciences (and as such, are persuaded to develop highly quantitative specifications). DMA's production staffs, on the other hand, are rich in years of graphic arts experience. The result of the blends of thinking represented by these two poles of experience has, to date, seen the generation of extraordinarily demanding quantitative equipment specifications.

The key performance issue is the accuracy to which a specific location may be located on a full size graphic. At all of the DMA production centers, the "need" for 1 mil (0.001 inch) accuracy is verbally stated, although the written chart and map accuracy standards are generally more like 1/50 inch (0.020 inch). In fact, the real requirement for accuracy is derived from registration tolerances when from 3 to 5 (or more) separation negatives must be superimposed. A few symbols of a bifilar nature such as roadways with color fill and road or railway bridges are the most demanding, and misregistration of the order of 3 to 6 mils (0.003 to 0.006 inches) are discernible by most human observers at normal viewing distances. What, then, should be demanded as the accuracy requirement for a master cartographic recorder?

We can show proof positive that 1 mil accuracy is adequate; in fact, it is more than adequate. Similarly, plots made to 7 mil accuracy can be shown to be inadequate for the multi-separation imposition of most cartographic products. In terms of human acuity, even considering that cartographic products are viewed and used at short eye-to-graphic working distances, a 2 mil accuracy will be adequate for normal unaided viewing. (Human eye resolving power is 0.80 arc minutes for a 50% detection probability; 2 mils at a close working distance of 10 inches subtends 0.69 arc minutes and is below this threshold.)

Extrapolating this accuracy requirement to full size graphics to be produced by magnification from EBR microform images, then, tells us that an EBR working at an accuracy of 16,000 addressable points will allow for the accurate production of charts 32 inches in linear dimension. Thus, JOG size sheets*, the predominant cartographic product size in DMA, may be readily produced from EBR microform graphics from the standpoint of reliable EBR accuracy.

*Map dimensions 17 x 23 inches within work limits of 22.125 x 28.50 inches and paper trim size of 22.50 x 29.00 inches; scale = 1:250,000.

2.1.6 CONSIDERATIONS FOR APPLICATION OF EBR TECHNOLOGY IN THE PRODUCTION ENVIRONMENT

This section addresses the developments required to render the large format, high resolution electron beam recorders which have been produced to date to a higher level of product maturity and reliability, as well as aspects of the technology which require careful consideration in installation and application.

2.1.6.1 Photographic Recording Media - Early during the development of direct electron film recorders, it was discovered that the dielectric effects of photographic film using conventional emulsion creation techniques, led to an unacceptable amount of film charging as a consequence of exposure to the electron beam.* This led to the development of films by Eastman Kodak in the U.S.A. and Ilford in England that had a conductive layer underneath the emulsion. This conductive layer precludes the build-up of charge as the electron beam writes the image across the format.

At the present time, the primary product available to users in the U.S.A. of this type of photographic film is Eastman Kodak's type SO-219 film. Its D log E characteristics are given in Figure 2-1. This film is characterized by a reasonably high speed and an extremely fine grain structure. This film has been used successfully for several years in high resolution, high geometric fidelity electron beam recording.

*Silver halide emulsion is conductive at 50% R.H., but is non-conductive at 0% R.H. (vacuum condition); the conductivity of the underlying coating approximates the nominal emulsion conductivity at 50% R.H.

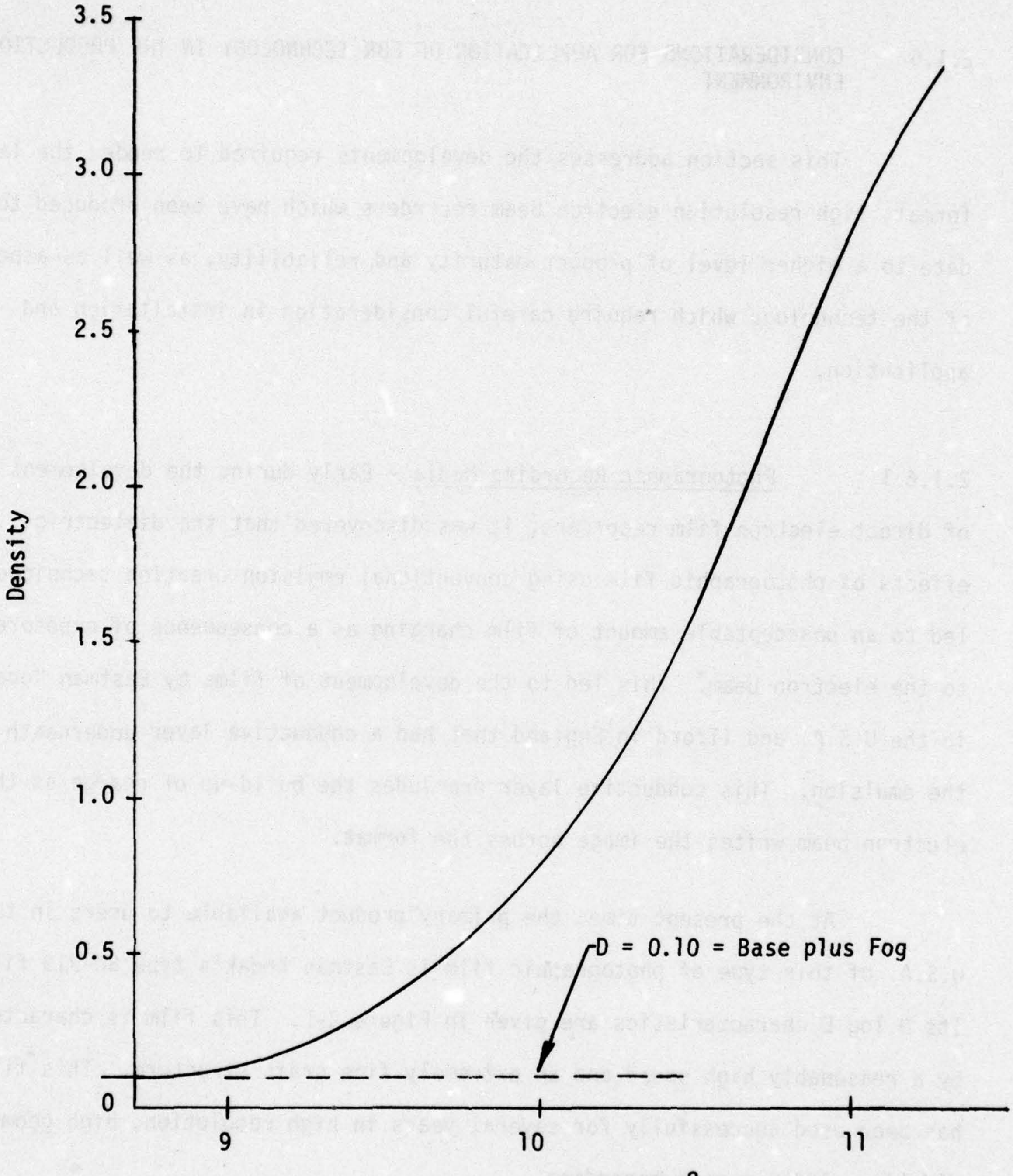


FIGURE 2-1

D-Log E CHARACTERISTICS OF KODAK

DIRECT ELECTRON RECORDING FILM, TYPE SO-219

Most users of electron sensitive film have been made aware, by the manufacturer, Eastman Kodak, that the availability of SO-219 film may be ended within the next twelve months*. The potential non-availability relates to the planned demolition of a building at Eastman Kodak in Rochester, New York which houses the specialized equipment used for applying the conductive undercoat to the Estar base. Due to the low throughput of this product, Eastman Kodak does not intend to re-establish the production facility elsewhere. An alternate film has been available for some time. Its designation is SO-438. It is a faster film, although possessing a larger grain size than SO-219, but the most important difference is the lack of the conductive coating under the emulsion. Experimental results have shown that the accumulation of charge on the emulsion of SO-438 can result in both geometric distortions and reduction of electron beam penetration into the emulsion which yields a reduction in film density for a given beam current delivered to the film plane.

*Most recently, Eastman Kodak has ensured its users that conductive film will continue to be available. The discussion of non-conductive film has been presented for a more complete picture of the nature of electron beam/film interactions.

An understanding of the charging mechanism may be gained by considering the film to be a series of tiny capacitors, each representing a data cell. In a system in which SO-438 film will be used, it is important to utilize a backing plate in the film plane which is completely continuous. This will result in the presentation to the electron beam of a uniform capacitance to ground by the film as a large array of capacitors. The effect of a non-uniform capacitance to ground has been experimentally observed in film platens which had vent holes drilled in them. In this case, a non-uniform capacitance to ground is presented and the outline of the holes is clearly visible in the output film. In the region of a hole in the film platen, the capacitance to ground will be decreased in proportion to the apparent film thickness measured from the point of electron beam landing to the nearest ground plane. This reduced capacitance will allow the local area of the non-conductive film to attain a higher potential as a result of electron beam charging. The higher potential will result in beam repulsion and reduced beam penetration, thus producing reduced film density.

When one considers that the greatest utility for the EBR microform outputs in the context of pressplate making is through the use of negative rather than positive images, this effect can be considered serious. From the point of view of desiring to minimize the charge build-up on a frame of electron sensitive film, one would conclude that the most desirable product output would be a film positive. Consequently, photographic reversal processing has been explored and successfully demonstrated.

2.1.6.2 Proof Plotting - Plotting proofs from digital data tapes is a crucial operation, and one in which economies of both scale and material should be exploited. Serious consideration is being given to the utilization of the newly emerging electrostatic recording media for EBR proof plotting.

2.1.6.3 Other Considerations - In the successful application of an electron beam recording device in a production environment, consideration must be given to operator safety as both high voltages in the electron acceleration process and high temperatures in the vapor diffusion pump processes are present. These issues are normally addressed by physical protection and safety interlocks which preclude the operator from coming in contact with dangers, and are less formidable than the hazards of home television receivers.

Preventative maintenance of this type of equipment is a key consideration in its application in a production environment. There are several known areas in which preventative maintenance can dramatically enhance the utility and uptime of an electron beam recorder. These include scheduled maintenance for the vacuum system components such as oil changes in the oil vapor diffusion pumps, oil changes in the mechanical pumps, and general system inspection and maintenance record keeping. Scheduled maintenance replacement of the thermionic electron source is another consideration. The electron source should be designed to be modular in fashion and require a minimum of downtime in reinstallation and realignment.

2.2 TRANSFORMATION OF MICROFORM GRAPHICS INTO CARTOGRAPHIC PRODUCTS

Before describing in detail the techniques by which EBR output microform graphics can be transformed into cartographic products, it is useful to describe the present technique in which full scale graphics are utilized to produce pressplates and eventually press runs of cartographic products.

At the present time, in the production centers, the data base can be a combination of textual survey data, photographic information, digital records, and other forms of input. These are reviewed by analysts and combined in a fashion suitable for a draftsman or engraver to prepare base sheets and topographical overlays. The imposition of names and data has become reasonably automated with provisions made for a hierarchy in which the most important data are placed with the greatest proximity to the feature which they describe. The engraved and photoimposed separations are combined and merged into large sheets of film which form the color separation negatives from which individual wipe-on diazo pressplates are contact exposed generally using carbon arc light sources.

Solid areas of various colors are produced by using conventional photographic screening processes. DMA is currently in the process of standardizing at 120 line per inch screens. Consideration has been given to the capability of electron beam recording technology to produce "electronic screening". This technique, while completely feasible, will, in general, cause the design of an electron beam recording device that substantially over-resolves the typical line weights used in order that it can accomplish high resolution screening. It will primarily be useful in products in which the total number of data points across the maximum dimension fall substantially short of the approximately 2^{14} spot diameters presently considered feasible for the electron beam recorder to support in a production environment.

2.2.1 PROJECTION PLATEMAKING

A number of approaches for making pressplates from various microforms have been developed. Of these approaches, some have proven to be more viable than others.

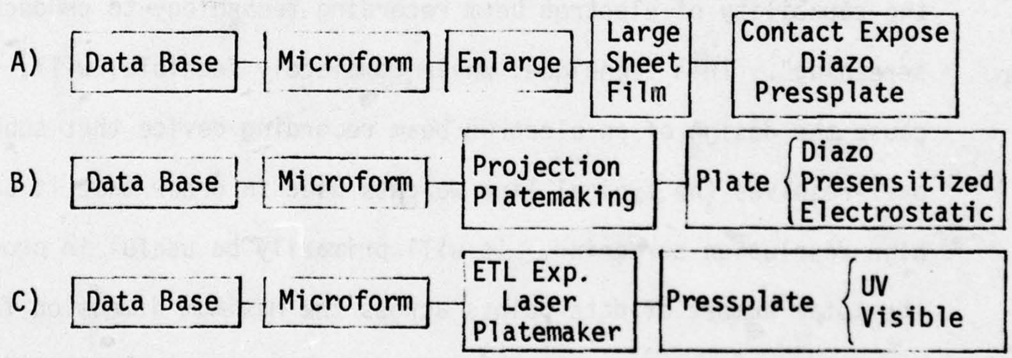
The types investigated in this study fall into three categories. They are:

Projection Platemaking

Laser Platemaking

Ink Jet Methods

In the category of projection platemaking, three techniques have received the most interest. These techniques are shown schematically in the figure below:



The first technique, A, uses an intermediate image carrier. The data base is used to generate a microform. This microform is then projected onto a large sheet of film such that the projected image is the same size as the desired pressplate image. The image is transferred from the film to the diazo pressplate by direct, contact exposure of the plate.

The second technique, B, eliminates the need for the large area film by imaging the microform directly onto the pressplate. In many cases, the pressplate has been presensitized so that the amount of energy necessary to expose a unit area of the plate is substantially reduced.

The third technique, C, is similar to B above in that light passing through the microform is used to directly expose the pressplate. With this technique, however, the light source is a laser and the microform, acting as a spatial modulator, is scanned rather than flooded.

2.2.1.1 Materials Available - Many types of pressplate materials are currently available. Some of these are commonly used with projection techniques similar to A and B above. Other materials were, or are, being developed for use with laser projection systems like C above and with laser platemaking systems (see Section 2.2.2). It is not necessarily valid to assume that pressplates used with non-laser systems can be used, to any degree of success, with laser systems. The short "dwell time" of the light spot on a given picture element and the line overlap inherent in laser systems present

a unique set of exposure conditions to the pressplate material. For the qualitative analysis that follows, the reverse assumption, however, will be made, i.e., that pressplate materials designed for laser systems will exhibit similar characteristics when used in a projection (non-laser) system.

Some typical plate materials are presented in Table 2-2. Also presented are the exposure characteristics of these plates. While only a small fraction of the materials available are shown in this figure, the exposure and spectral characteristics of these materials are representative of what is available, and describe the bounds of required exposure values.

TABLE 2-2

EXPOSURE CHARACTERISTICS OF TYPICAL PRESSPLATE MATERIALS

Manufacturer	Product Name	Typical Exposure Required (Joules/cm²)	Spectral Sensitivity
(1) GAF Corp.	Ozachrome	~ 1	U.V.
(2) Richardson	S-85, S-160	0.1	320 - 420 nm
(2) Anonymous	Experimental Laser A	0.1	IR
Kodak	KRL-X	3×10^{-2}	$\sim$ 360 nm
(2) Horizons	Experimental Resist	$(15\text{-}20) \times 10^{-3}$	U.V. - 360 nm
(2) 3M	Experimental Laser	$(5\text{-}20) \times 10^{-3}$	U.V. and/or Visible
(2) Western Litho	Litho Laser	$(5\text{-}10) \times 10^{-3}$ $(15\text{-}150) \times 10^{-3}$	U.V. Visible
(2) Anonymous	Experimental Laser B	1×10^{-3}	U.V. and/or Visible
(2) 3M	Pyrofax	2.5×10^{-6}	Unavailable
Coulter	KC-Film	5×10^{-7}	Visible

(1) Bader, T.R., Investigation of Cartographic Pressplate Recording from Digital Data, Harris Corporation Electronic Systems Division, Contract Report on Contract DAAG53-76-C-0021.

(2) Kelly, Stephen, Digital Data to Pressplate Study, Technical Report, Mead Technology Laboratories, Final Contractor Report on Contract DAAG53-76-C-0022.

2.2.1.2 Non-Laser Projection Systems - A typical non-laser projection system is presented schematically in Figure 2-2. As shown in this figure, light from a high intensity source is collected and directed toward the EBR film plane through the use of parabolic and/or spherical mirrors. Prior to reaching the object plane, the light may pass through a series of dichroic mirrors and/or specially designed filters. The purpose of these elements is to remove that spectral portion of the light that does not match the spectral sensitivity of the plate or film being exposed. These elements thus serve to reduce the amount of film heating associated with the exposure process. The remaining portion of the light is then passed through beam shaping optics (condenser lens, etc.) and directed onto the EBR film. This light is thus used to project the film image through the use of projection optics onto the plate or film being exposed.

Of interest in analyzing such a projection systems is the relationship between the required exposure of the "plate" plane, the amount of energy loss at the EBR film plane (film heating), and the required power of the light source. To establish these relationships, a mathematical model for this type of projection system was developed and is derived in Appendix A. The mathematical expressions for the signal, S, at the plate plane, the average irradiance, $\bar{I}'$, at the plate plane, and the irradiance, I, at the film plane are presented below. S(K') is used for the signal term to denote signal as a function of spatial frequency in the image (plate) plane.

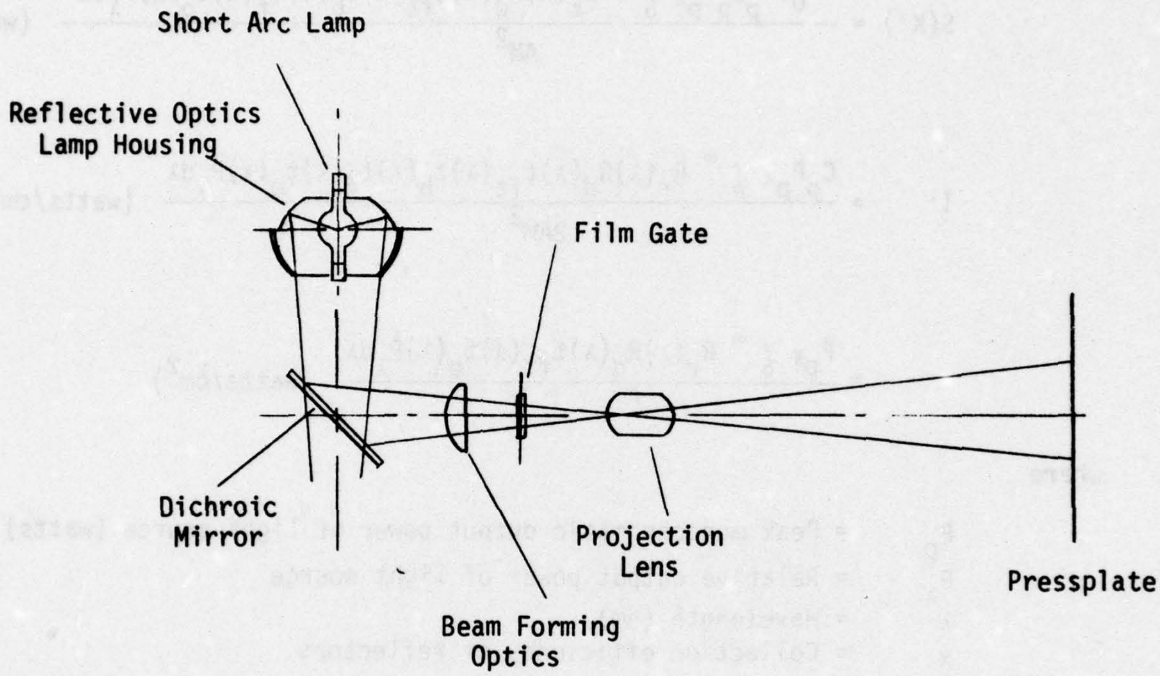


FIGURE 2-2

NON LASER PROJECTION SYSTEM

$$S(K') = \frac{M_o \tau'_p C_p P_p \chi \int_0^\infty R_r(\lambda) R_d(\lambda) t_{ft}(\lambda) t_b(\lambda) t_f(\lambda) t_p(\lambda) P_\lambda d\lambda}{AM^2} \quad (\text{watts/cm}^2)$$

$$I' = \frac{C_p P_p \chi \int_0^\infty R_r(\lambda) R_d(\lambda) t_{ft}(\lambda) t_b(\lambda) t_f(\lambda) t_p(\lambda) P_\lambda d\lambda}{2AM^2} \quad (\text{watts/cm}^2)$$

$$I = \frac{P_p \chi \int_0^\infty R_r(\lambda) R_d(\lambda) t_{ft}(\lambda) t_b(\lambda) P_\lambda d\lambda}{A} \quad (\text{watts/cm}^2)$$

where

P_p = Peak monochromatic output power of light source (watts)
P_λ = Relative output power of light source
λ = Wavelength (nm)
χ = Collection efficiency of reflectors
$R_r(\lambda)$ = Reflection coefficient of reflectors
$R_d(\lambda)$ = Reflection coefficient of dichroic mirror
$t_{ft}(\lambda)$ = Transmission coefficient of filters
$t_b(\lambda)$ = Transmission coefficient of beam shaping optics
$t_f(\lambda)$ = Transmission coefficient of film (base + fog)
$t_p(\lambda)$ = Transmission coefficient of projection optics
C_p = Collection efficiency of projection optics
A = Illuminated area at film plane (cm^2)
M = Linear magnification ratio
τ'_p = Spatial response (MTF) of projection optics (line pairs/mm)
M_o = Modulation associated with film contrast

For a given required exposure (joules/cm^2), dictated by the characteristics of the chosen plate or film, a certain amount of energy will be absorbed by the EBR film. The magnitude of this energy, along with the effectiveness of a given film cooling approach will determine the extent to which the film will expand during the exposure process. The amount of film expansion is of concern since it can lead to unacceptable line-broadening and dimensional distortion on the plate or film. This concern can, in turn, influence such factors as plate or film selection and exposure time for a fixed exposure.

The results of film expansion due to heating will be very slightly ameliorated by a film shrinkage which will occur simultaneously with the initial film heating. This effect is produced by the reduction in moisture content of the film which is expected to accompany the film heating. In general, however, the magnitude of the moisture content change will be far less than the magnitude of the temperature change. Considering the similarity of the expansion and contraction coefficients involved for temperature and humidity changes, the effect of changes in moisture content have not been included in the first order analysis presented in the following paragraphs.

2.2.1.2.1 Intermediate Image Carrier Projection Systems - As discussed in Section 2.2.1 above, the Intermediate Image Carrier approach uses the projected image from the EBR film to expose a large sheet of film. This exposed film is then used to contact expose the printing plate. This approach is undesirable from the standpoint that it adds an extra step into the overall process and uses up large quantities of photographic film. However, from the standpoint of EBR film heating and expansion, the small amount of total energy required to expose the film makes this approach quite attractive. For example, the typical exposure requirements for photographic film is of the order of 10 ergs/cm^2. Even assuming no cooling of the EBR film during the exposure process, the estimated increase in film temperature would be only 0.1 °F. This, in turn, would correspond to a maximum increase in film dimension of 0.01 mils in the 8" direction. Expansion of the large area film during contact exposing of the printing plate is also of little concern. While much greater energy densities are required for the subsequent exposure of the plate (as much as 1 joule/cm^2), the film is in direct contact with the plate. This serves two advantages. First, the plate serves as a type of "heat sink" to minimize the temperature increases. Second, any expansion of the film due to an increase in its temperature is partially compensated for by a corresponding expansion of the plate itself.

2.2.1.2.2 UV Projection Systems - A number of UV projection systems are, or have been, on the market. These systems are designed to expose plates directly, that is, without the use of an intermediate image carrier. These systems generally fit the configuration shown schematically in the figure presented in Section 2.2.1.2 and can be represented by the generalized mathematical model presented in that section. One such system has been developed by Latady Instruments*. Two variations of this system are presented below for the purpose of illustrating the potential problems that are associated with such a design.

In the first design, the light source is a 3500 watt Hanovia mercury-xenon arc lamp. A rear reflector is used to collect and project the light from the rear of the arc to the condensing lenses. A specially designed, three-element quartz condensing lens gathers the light and corrects for cosine fallout.

The projected light then passes through a specially prepared Schott KG-1 heat absorbing glass and a Schott BG-37 red absorbing glass. The filtered light, now predominantly UV and violet-blue is projected onto the film plane where, through the use of a specifically designed UV planar lens, it is used to project the film image onto the pressplate. With this system, up to 11X linear magnification of 70 mm film chips can be achieved.

As discussed earlier, film heating is of concern in such a system. This concern is dramatically illustrated in Figure 2-3 . In this figure, the increase in film temperature and corresponding line broadening or smear is

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*Latady Instruments Incorporated, Hingham, Massachusetts.

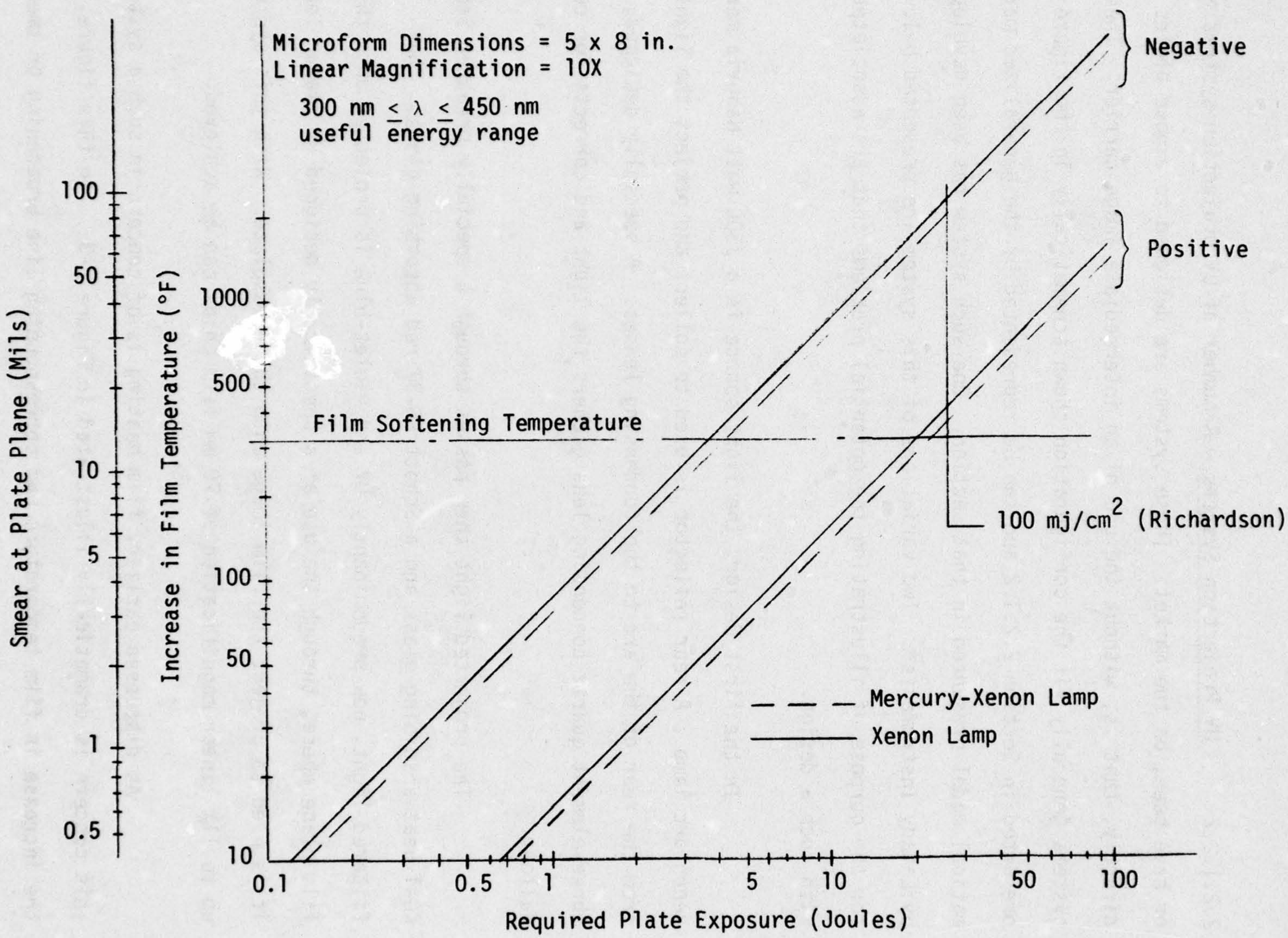


FIGURE 2-3

MAXIMUM FILM HEATING AND SMEAR FOR UV PROJECTION SYSTEM WITH HEAT FILTERS

presented as a function of required plate exposure for a no film cooling condition. These curves were generated using the model developed in Appendix A and making the assumption that the system can be modified to handle the 5" x 8" film from the cartographic EBR. Two other factors were varied parametrically in this analysis -- the type of light source used and whether the EBR film image is a positive (mostly transparent) or a negative (mostly absorbing).

This analysis is not intended to suggest that film temperature of these magnitudes will actually be achieved. Sophisticated film cooling techniques can and have been employed to remove much of the heat from the film. However, the analysis does point out that, unless very sensitive pressplate materials and/or lower magnifications are used, cooling techniques that remove even as much as 80% of the heat generated in the film are still inadequate to prevent unacceptable line broadening especially when film negatives are being used. The upper bounds of the film temperature shown in Figures 2-3 through 2-5 are not achievable in operation; they are shown primarily to emphasize the large rate of heat transfer which will be required from a film cooling system.

While not directly related to film heating, an estimate, using the mathematical model, of the energy absorbed by the heat absorbing glass and red absorbing glass points out the demands that must be placed on the cooling units for these elements. For instance, for a modest 0.1 joule/cm^2 plate exposure requirement, the amount of energy absorbed by each of these elements is:

Heat absorbing glass, mercury-xenon source:	110,000 joules
Heat absorbing glass, mercury source:	32,000 joules
Red absorbing glass, mercury-xenon source:	19,000 joules
Red absorbing glass, mercury source:	20,000 joules

The values used for the various model parameters in obtaining these energy values are presented along with the model in Appendix A.

The second design used by Latady Instruments replaces the heat absorbing and red absorbing glasses with a dichroic mirror. This mirror is designed to reflect the 250 to 450 nanometer portion of the spectrum and transmit all longer wavelengths. This approach has the advantage that the removal of the spectral portion of the light that does not match the spectral sensitivity of the plate is achieved not through absorption, but through the use of selective transmission and reflection. In addition, the dichroic mirror is more efficient than the absorbing glasses in removing the longer wavelength portion of the light from the film plane. However, the dichroic mirror selected in this particular case passes light in the 250-300 nm, as well as in the 300-450 nm, region. These wavelengths are almost completely absorbed by the film and add only to film heating, not to the plate exposure process. The result is that, while the cooling requirements for the elements between the light source and film gate are substantially reduced, the demands on any film cooling technique are still formidable. This fact can be seen in Figure 2-4 . The graphs presented in the figure are the result of repeating the film heating analysis discussed above, but this time substituting the dichroic mirror for the absorbers.

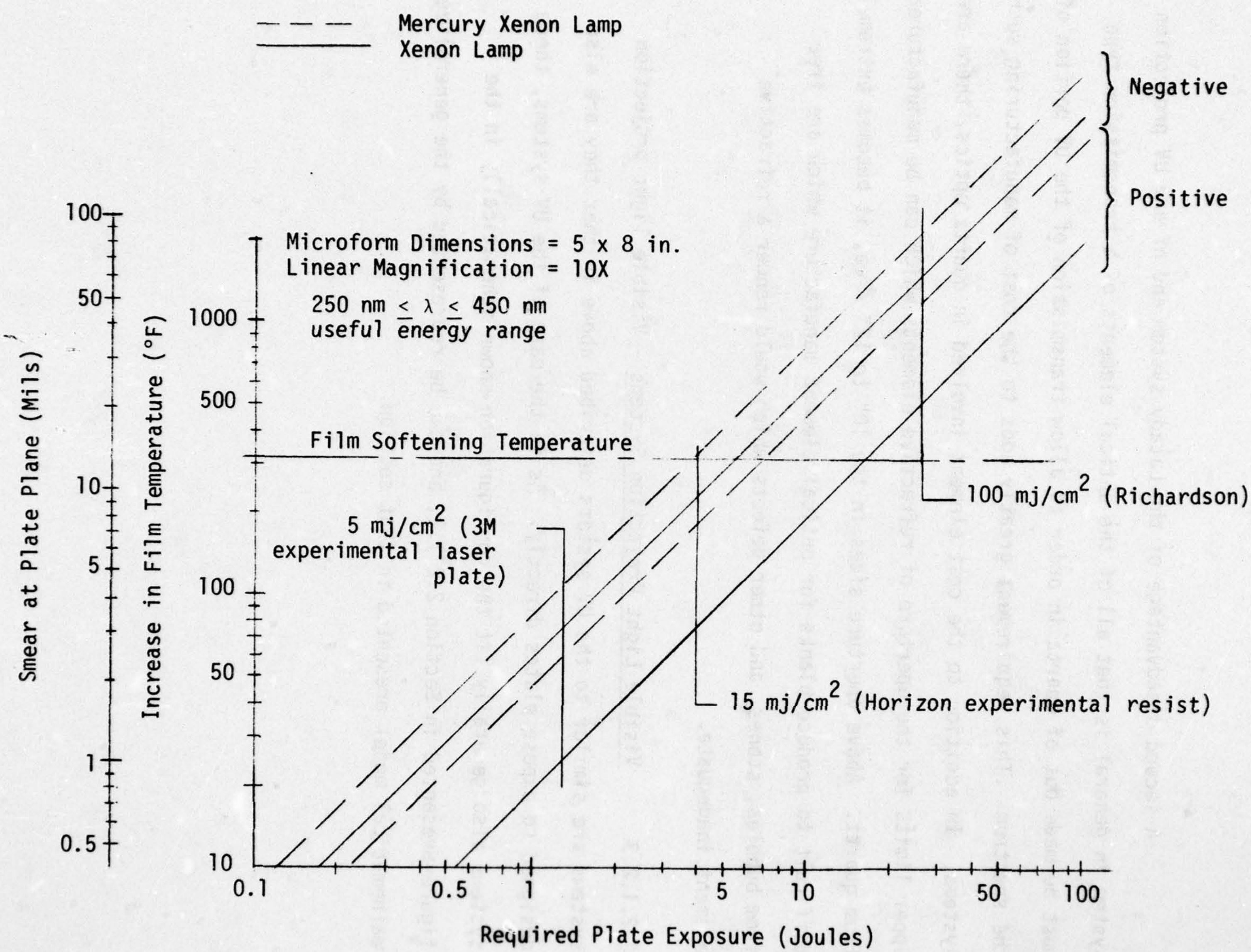


FIGURE 2-4

MAXIMUM FILM HEATING AND SMEAR FOR UV PROJECTION SYSTEM WITH DICHROIC FILTERS

A second disadvantage of the Latady system and of any UV projection system in general is that all of the optical elements of a transmission type must be made out of quartz in order to allow transmission of the UV portion of the spectrum. This requirement greatly adds to the cost of manufacturing such systems. In addition to the cost element involved in quartz optics, there are upper limits for the aperture of refractive elements which can be manufactured from quartz. Above aperture sizes in the 10" to 12" area, it becomes extremely difficult to produce blanks for optical element manufacture which are free from bubbles, stones, and other defects which would render a refractive element inadequate.

2.2.1.2.3 Visible Light Projection Systems - Visible light projection systems are similar to the UV systems described above in that they are also designed to expose plates directly. As in the case of the UV systems, these systems also generally fit the configuration shown schematically in the figure presented in Section 2.2.1.2, and can be represented by the generalized mathematical model presented in that section.

One visible light system which has received much attention is made by Opti-Copy*. This system is able to project film images having up to 8-1/2" x 11" formats to a magnification of 10X. The Opti-Copy system,as well as any of the other visible light projection systems,has at least two advantages over UV systems. First, they do not require the use of expensive quartz optics. Second, the transmission coefficient of the film is substantially higher in the visible portion of the spectrum. While this increase in film transmission leads to a reduction in the amount of film heating that will occur during a plate exposure, the amount of energy absorbed by the film is still very large. This can be seen in Figure 2-5 where maximum increase in film temperature and resultant line smear are presented as a function of plate exposure for visible light systems.

Several Opti-Copy systems were observed by the authors. The systems appear to be extremely well designed and are rugged and stable in optical alignment. Unfortunately, virtually all of the performance observations that have been made on this type of equipment are largely subjective in nature. It was the authors'observation that the Opti-Copy projector operating at blow-back magnifications of up to 10X produced extremely sharp line edge gradients and yielded acceptable geometric fidelity over very large formats. This statement, however, is completely subjective. It would appear of value to the Defense Mapping Agency to perform engineering tests using standard test patterns which would quantify the Opti-Copy projector modulation transfer function and geometric fidelity over large format areas.

*Opti-Copy, Inc., North Kansas City, Missouri

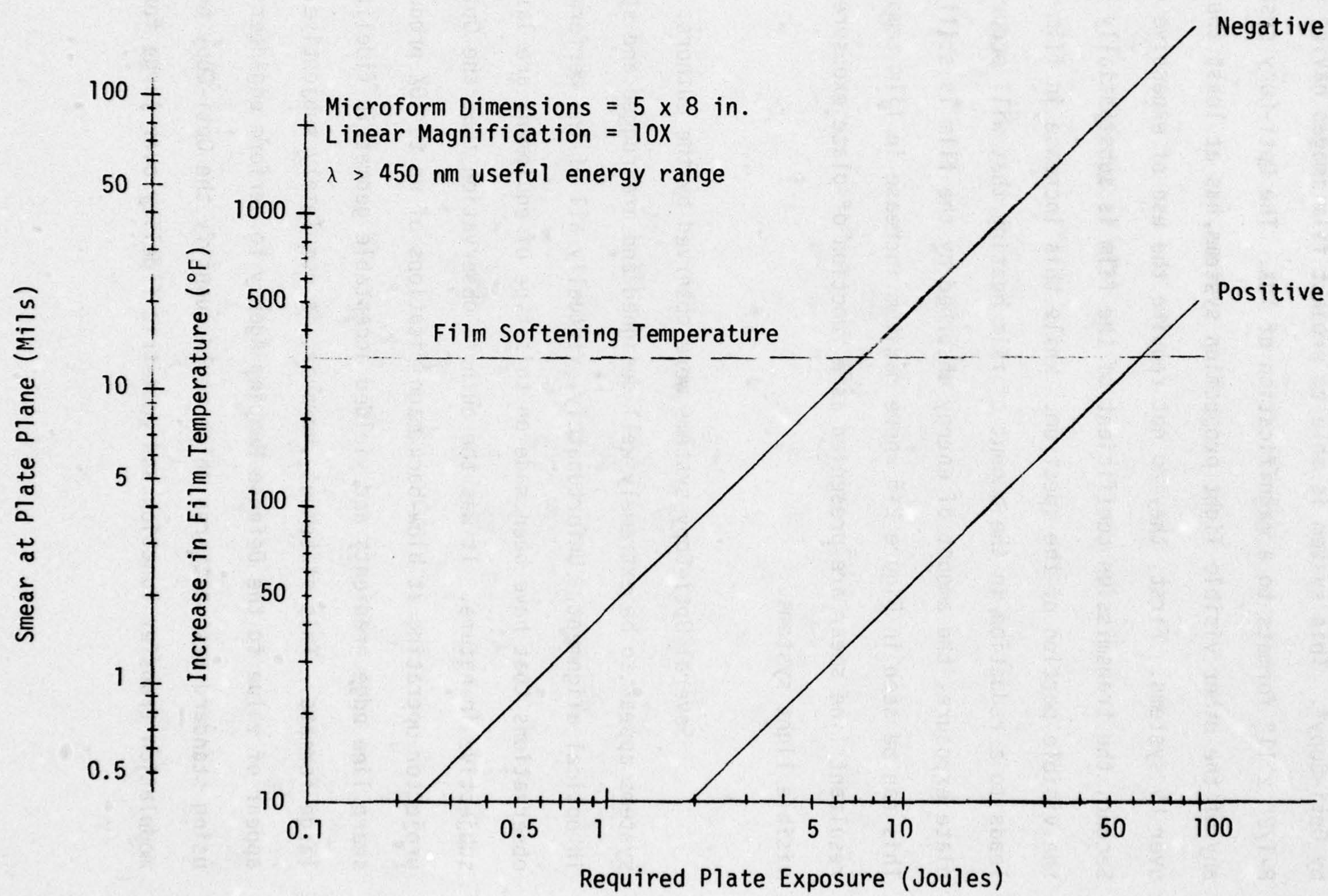


FIGURE 2-5

MAXIMUM FILM HEATING AND SMEAR FOR VISIBLE LIGHT PROJECTION SYSTEM WITH DICHROIC FILTERS

2.2.1.3 Laser Projection Systems - A unique laser projection system, developed at ETL, is illustrated schematically in Figure 2-6 . The uniqueness of this system is found in the scanning system and objective lens combination which result in the requirement for an objective lens of substantially smaller aperture than would be required in a conventional projection system. As shown in this figure, a light beam from the laser is passed through beam-shaping optics and directed toward an X-Y scanning system. The scanning system, which may be a set of orthogonal galvanometer mirrors, sweeps the light beam across the surface of a lens (lens #1) which, in turn, directs the beam to the film plane. In this way, the laser beam scans the surface of the film. As each element of the film is illuminated, that element is projected by the projection optics onto the pressplate material. It should be noted that this type of system does not work in the same way as laser scanning systems (see Section 2.2.2). That is, the light beam need not be focused into a small spot at either the film or plate plane. The EBR film, illuminated by the laser beam, serves as a spatial modulator and, as in the cases of the other projection systems discussed, its image is simply "projected" onto the pressplate.

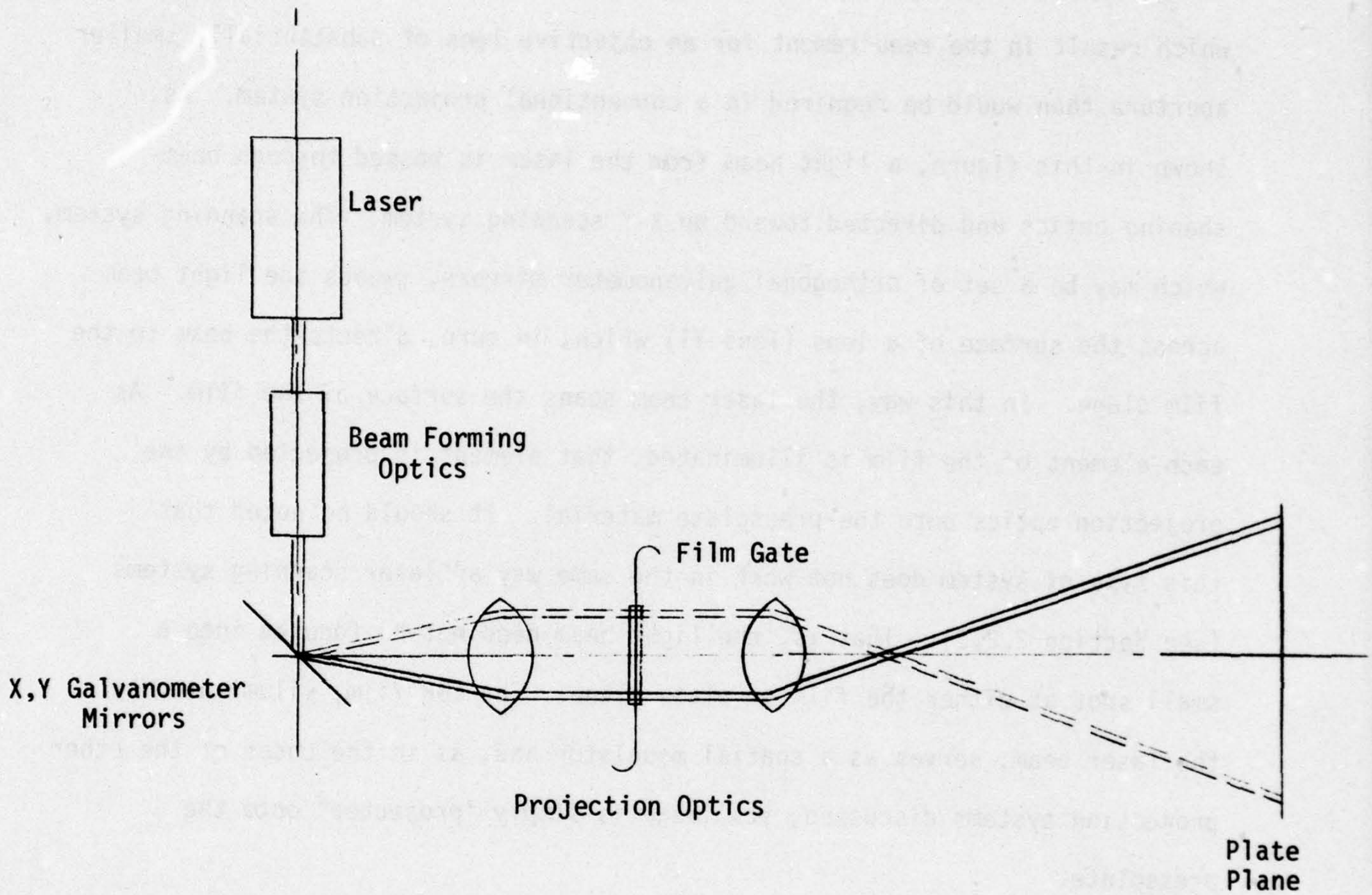


FIGURE 2-6

LASER PROJECTION SYSTEM (ETL)

Parallelling the analysis of the other projection systems, the relationships between the required exposure at the plate plane, the amount of energy loss at the EBR film plane, and the required power of the light source, are of interest in analyzing a laser projection system. Therefore, a mathematical model for this type of system was also developed and is drived in Appendix A. The expression for the signal, S, at the plate plane, the average irradiance, $\overline{I}'$, at the plate plane, and the irradiance, I, at the film plane are presented below:

$$S(K') = \frac{M_o \tau_p' C_p \sum_{i=1}^{n} t_b(\lambda_i) R_g(\lambda_i) t_{L1}(\lambda_i) t_f(\lambda_i) t_p(\lambda_i) P(\lambda_i)}{AM^2} \quad (\text{watts/cm}^2)$$

$$I' = \frac{C_p \sum_{i=1}^{n} t_b(\lambda_i) R_g(\lambda_i) t_{L1}(\lambda_i) t_f(\lambda_i) t_p(\lambda_i) P(\lambda_i)}{2AM^2} \quad (\text{watts/cm}^2)$$

$$I = \frac{\sum_{i=1}^{n} t_b(\lambda_i) R_g(\lambda_i) t_{L1}(\lambda_i) P(\lambda_i)}{A} \quad (\text{watts/cm}^2)$$

where

$P(\lambda_i)$ = laser output power at wavelength λ_i (watts)

λ_i = wavelength (nm)

$t_b\,(\lambda_i)$ = transmission coefficient of beam shaping optics

$R_g\,(\lambda_i)$ = reflection coefficient of the galvanometer mirrors

$t_{L1}(\lambda_i)$ = transmission coefficient of lens #1

$t_f(\lambda_i)$ = transmission coefficient of film

$t_p(\lambda_i)$ = transmission coefficient of projection optics

C_p = collection efficiency of projection optics

A = area of laser beam spot at film plane (cm^2)

M = linear magnification ratio

τ_p' = spatial response (MTF) of projection optics (referred to plate plane)

M_o = modulation associated with film contrast

By making numerical substitutions into this model, an estimate of film heating under a "no film cooling" condition was also made. The results of this analysis are presented in Figure 2-7 . It will be noted that, compared to other projection systems, the amount of film heating using this type of system is substantially less. This is primarily due to the assumption that the collimated nature of the laser beam gives the projection lens a much higher collection efficiency. While substantially less, the amount of heat absorbed by the film can still be sufficiently high to require the use of film cooling techniques.

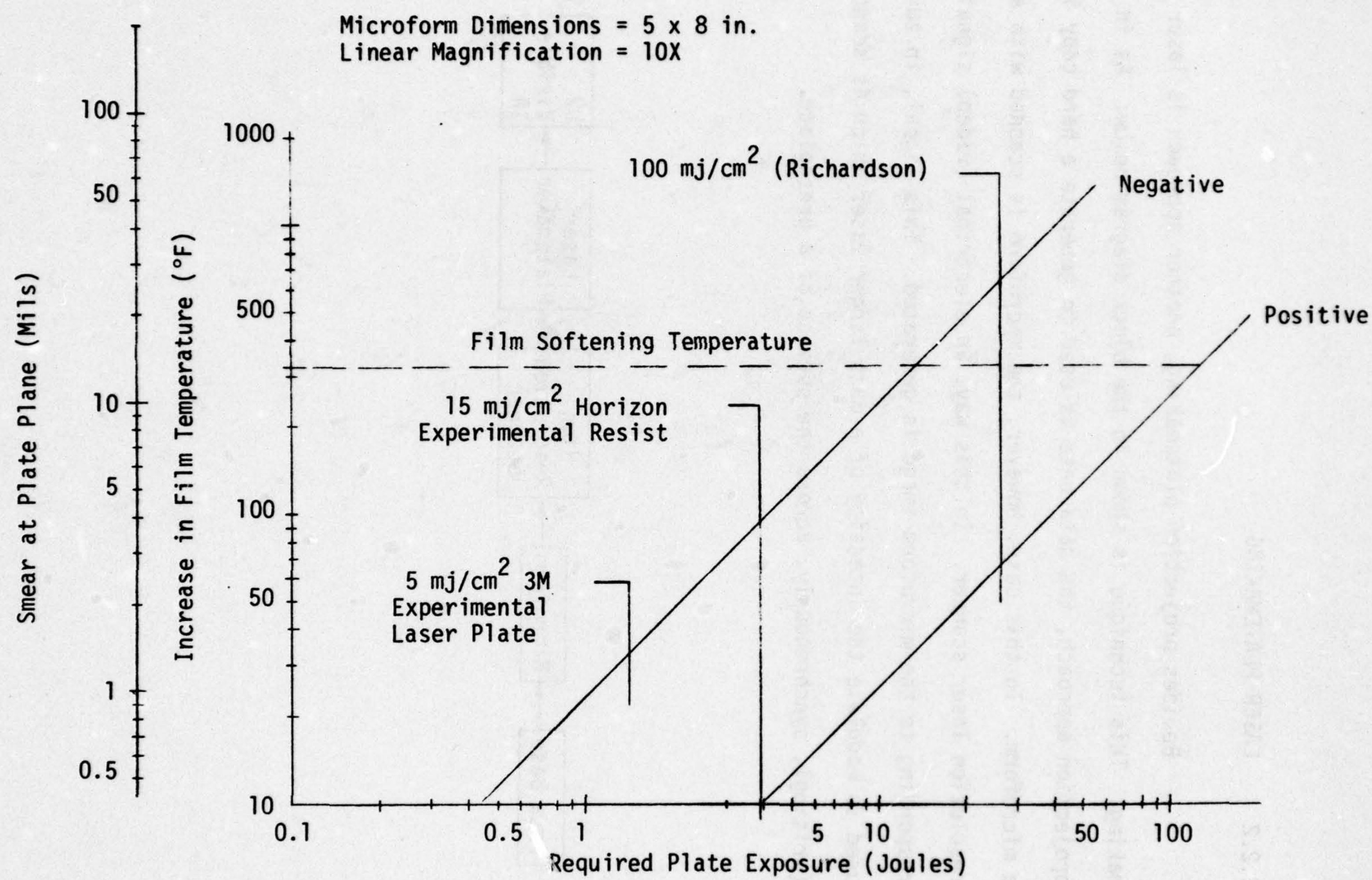
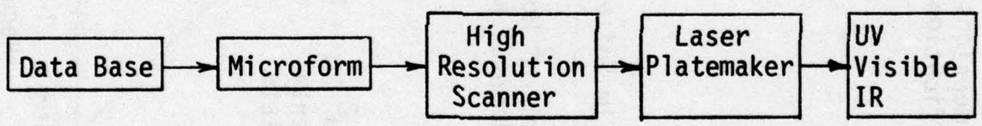


FIGURE 2-7

MAXIMUM FILM HEATING AND SMEAR FOR LASER PROJECTION SYSTEM

2.2.2 LASER PLATEMAKING

Besides projection platemaking, another approach is laser platemaking. This technique is shown in the block diagram below. As in the projection approach, the data base is used to generate a hard copy image on a microform. In this case, however, the microform is scanned with a high resolution laser scanner. In this way, an electrical (video) signal corresponding to the microform image is generated. This signal, in turn, is used to modulate the intensity of a much larger laser which is scanning (writing), synchronously, across the surface of a pressplate.



The scanning out/writing-in portion of this technique is presented in more detail in Figure 2-8 . As can be seen from this figure, scanning out of the microform image is accomplished in much the same way as it is done in the laser projection system. The principal difference is that here all of the light passing through the microform is collected and imaged onto a photomultiplier tube (PMT). Thus, unlike the projection system, all information as to where the light was transmitted on the microform is lost. Consequently, to retain the information content of the microform, a very small light spot (a fraction of the size of the smallest detail to be resolved) must be used. To achieve this small spot over the entire microform surface, sophisticated optics are necessary. A similar requirement applies to the area of the spot being used to expose the pressplate. It, too, must be a fraction of the size of the smallest detail to be resolved <u>on the pressplate</u>.

The basic components of the "write-in" portion of the system are similar to the "scanning out" portion. The main difference is that the high energy laser in this portion of the system is modulated by the video signal from the PMT.

A mathematical model for a laser platemaker is derived, along with the other models, in Appendix A . The expressions for the parameters of interest are presented below.

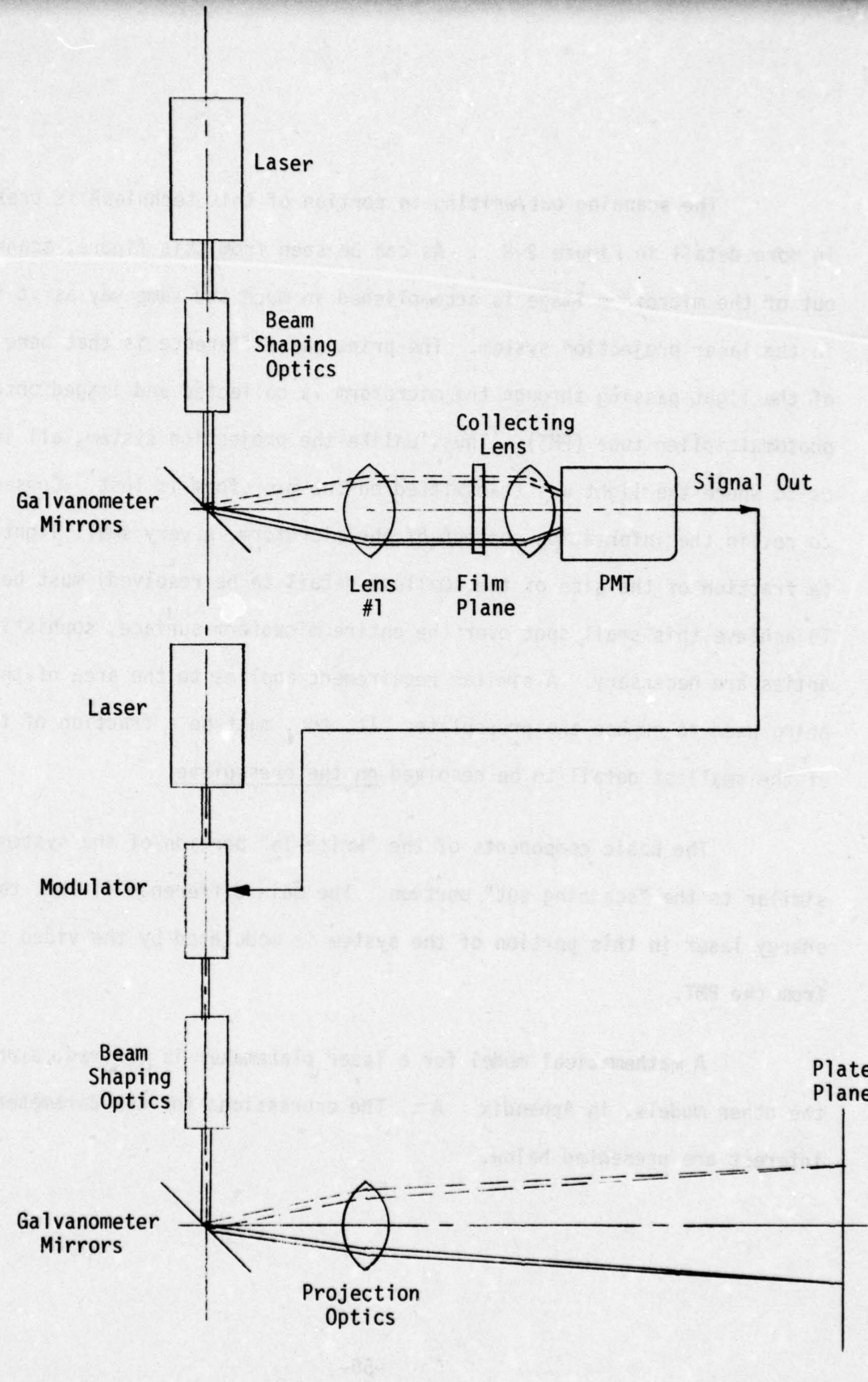


FIGURE 2-8

LASER PLATEMAKING SYSTEM

$$S(K') = \frac{\tau_p' \sum_{i=1}^{n} t_m(\lambda_i) t_b(\lambda_i) t_g(\lambda_i) t_p(\lambda_i) P(\lambda_i)}{A_2} \quad \text{(watts/cm}^2\text{)}$$

$$\bar{I}' = \frac{\sum_{i=1}^{n} t_m(\lambda_i) t_b(\lambda_i) t_g(\lambda_i) t_p(\lambda_i) P(\lambda_i)}{2A_2} \quad \text{(watts/cm}^2\text{)}$$

$$S(K) = \tau_{L1} M_o G_m S_p \sum_{i=1}^{n} t_b(\lambda_i) t_g(\lambda_i) t_{L1}(\lambda_i) t_f(\lambda_i) t_c(\lambda_i) \sigma(\lambda_i) P(\lambda_i) \quad \text{(amps)}$$

$$I = \frac{\sum_{i=1}^{n} t_b(\lambda_i) t_g(\lambda_i) t_{L1}(\lambda_i) P(\lambda_i)}{A_1} \quad \text{(watts/cm}^2\text{)}$$

where the terms are defined in Section 2.2.1.3 and below:

$S(K)$ = signal out of the scanner (amps)

$t_m(\lambda_i)$ = transmission of modulator in "on" mode

A_2 = area of "write-in" laser spot (cm^2)

$\sigma(\lambda_1)$ = relative photocathode response

$t_c(\lambda_1)$ = transmission of collecting lens

S_p = peak monochromatic photocathode response (amps/watt)

G_m = PMT multiplier gain

M_o = modulation associated with film contrast

τ_{L1} = spatial response (MTF) of lens #1 (referred to film plane)

A_1 = area of "scanning out" laser spot (cm^2)

The principal advantage of this type of system over the projection systems is that an insignificant amount of energy is absorbed by the microform during the scanning out process. The amount of power in the light beam scanning the microform need only be large enough to generate a video signal having an associated signal-to-noise ratio greater than about 10:1. Such a signal characteristic can generally be realized using low noise lasers in the 5-20 milliwatt range.

On the other hand, systems of this type tend to be considerably more complex. In essence, these systems are comprised of two scanners instead of one. Therefore, two lasers and a duplication in some of the optics are needed. Also, in order to maintain the small scanning spot over the entire surface of the microform, precise alignment of the optics must constantly be maintained.

A second disadvantage of this type of system is the fact that it exposes the pressplate on an element-by-element, line-by-line basis. This is in contrast to a projection system which exposes either the entire plate or, in the case of a laser projection system, at least many elements simultaneously. Depending upon the power of the write-in laser, this serial method of plate exposure can lead to very long exposure times. This fact is shown graphically in Figure 2-9 . In this figure, the exposure time versus laser power is plotted for a series of pressplate materials. These plots were obtained using

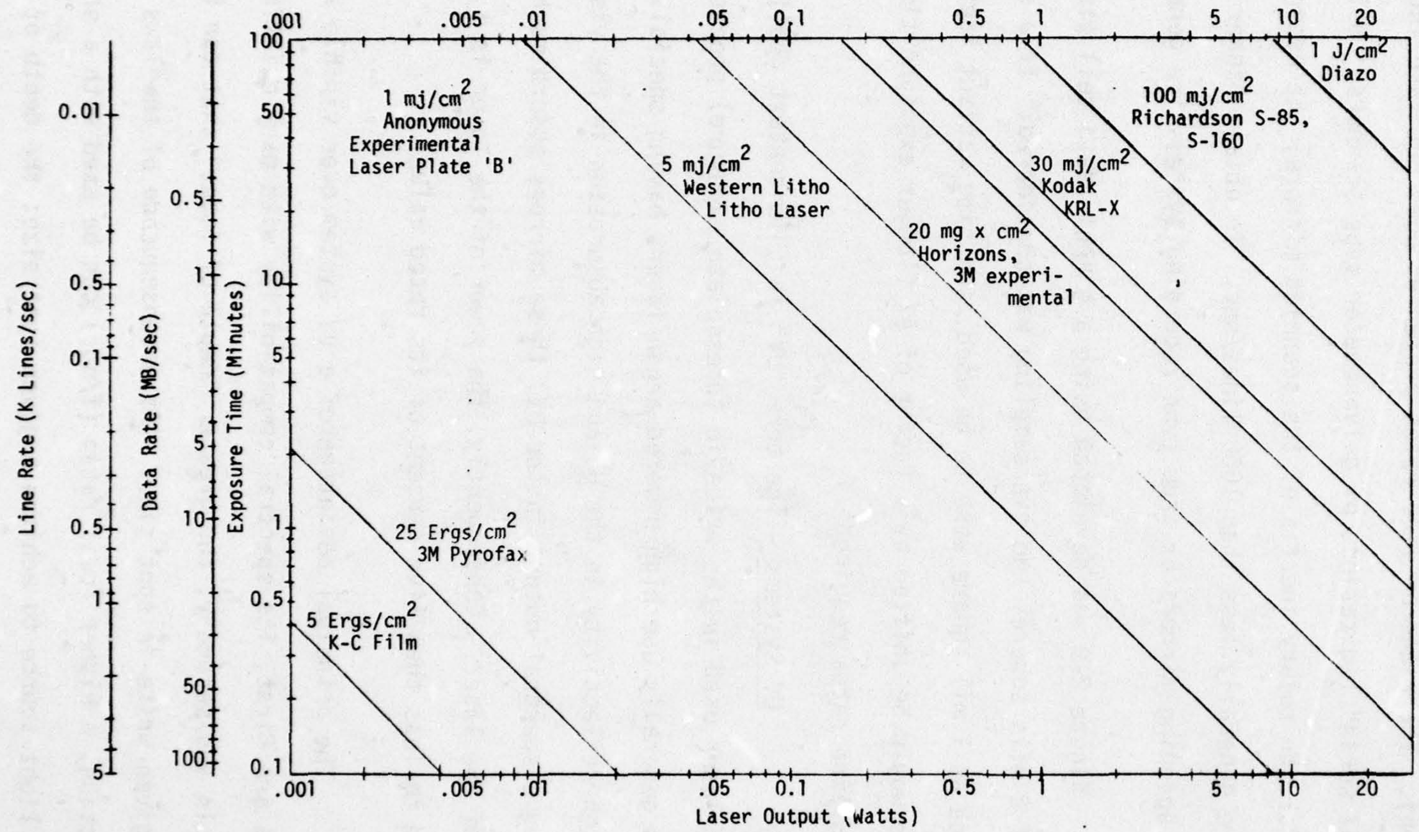


FIGURE 2-9

EXPOSURE RATES FOR LASER PLATEMAKING SYSTEMS

the mathematical model developed in Appendix A, assuming a good spectral match between the laser and plate material, and assuming a 44" x 60" plate format. Also shown in this figure is the data (bit) rate and line rate corresponding to a given exposure time (defining a "line" to be in the 44" direction). The range of line rates presented does not take into account the "real world" limitations of galvanometer type scanners. Using typical values for the rotary inertia of the scanning mirrors, the associated line rates are generally less than 1000 lines/sec. To obtain higher rates, multi-faceted spinning mirrors or drum type recording systems are generally used.

Figure 2-9 was developed using a graphic data cell size on the press plate of 2 mils square. No oversampling was considered. If a smaller data cell such as 1 mil square were to be used, the time variant factors on the ordinate would be shifted by a factor of 4X (longer exposure times, higher data and line rates required).

2.2.2.1 *UV Systems* - The term "UV" in this context applies to the type of laser used in the write-in (pressplate exposure) process only. These systems generally use high powered argon lasers having specially coated mirrors with high reflectivity in the UV and high absorption in the visible. While yielding a spectral output in the UV, these mirrors absorb much of the output power of the laser. Consequently, the power of the laser is typically reduced to less than five percent of its rated value.

The principal advantagesof a UV system over visible and infrared systems are first, its spectral compatibility with many existing pressplate materials and secondly, the greater "depth of focus" that can be realized for a given write-in spot size. (As a consequence of the laws of physical diffraction, a higher focal ratio (f/no.) can be used with a shorter wavelength light source to achieve a given spot size; the depth of focus is proportional to the square of the focal ratio.)

The principal disadvantage of a UV system is that argon lasers, at the present time, are not as stable and reliable as some of the lasers that can be used in visible and IR systems. Consequently, greater maintenance and repair efforts may be associated with such a system.

Among the UV laser scanning systems currently on the market is one manufactured by EOCOM Corporation* called LASERITE™. However, this system, designed primarily for the newspaper industry, scans out paste-ups rather than film. A small helium-neon laser is used in the scanning-out process. Their particular design allows much of the optics to be shared by both the helium-neon and UV (argon) lasers. This approach, therefore, reduces the complexity of this system and minimizes the alignment procedures. In addition, each laser scans only in one direction (e.g., across the page). Scanning in the other direction is achieved by moving the paste-up and pressplate under the scanning beam. This method of scanning further reduces the complexity of the system.

2.2.2.2 Visible Light Systems - The major advantage of visible light systems is that the lasers available for such systems are generally more stable and reliable that UV lasers. Thus, these systems, when compared to UV systems, should require less maintenance and repair.

The major disadvantages are smaller depth-of-focus and a smaller selection of pressplate materials that are spectrally compatible with visible light systems.

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*EOCOM Corporation, Irvine, California

2.3 DMA PRODUCTS

The product mix of the DMA production centers is extreme and is a function of the output requirements of each of the individual centers. In particular, the greatest divergence of product size mix occurs at the Hydrographic and Aeronautical Centers. In both of these centers, there are a series of frequently updated "book-like" products which are of prime importance to their users. These products include such publications as notice to mariners, light lists, and air information products (with the exception of en route charts).

At the present time, most of the book-like publications are produced by typesetting machinery. It is quite conceivable, that the use of EBR technology as a form of electronic typesetting could significantly enhance throughput. In such a system, a 35 mm EBR would be most useful. In this film size, the publishing industry has available to it several high quality platemaking devices such as equipment produced by Pagination Incorporated and UMF Systems Incorporated. These systems allow for the step-and-repeat pagination exposure of pressplates for a variety of computer-controlled pagination arrangements.

The production of charts and maps certainly impose most of the technical challenge in terms of master recorder resolution and recording speed. Consideration has been given in this study to the wisdom of attempting to exploit one technology as a master recording technology for such a wide mix of products. The conclusions of these considerations and recommendations for EBR technology exploitation are presented in Sections III and IV.

2.4 SPECIFIC PRODUCT STUDIES

At the outset of the study program, DMA expressed specific interest in certain product areas. In addition to those product areas specified by DMA, additional areas of potential EBR applicability arose during the conduct of the study. These product areas are discussed below.

2.4.1 COLOR SEPARATIONS

The majority of the map and chart products produced by the DMA as a whole are 1:250,000 scale graphics called Joint Operations Graphics (JOG). JOG size charts can readily be produced from EBR microforms using an optical magnification of the order of only 3.5:1 if a format such as the 5 x 8 inch cartographic EBR is used. Currently, JOG size products are printed two up at DMATC. Two-up imposition on a single plate is easily accomplished on available projection step and repeat equipment.

Full size separations, however, are not so simply handled. By "full size" color separations, we mean the maximum map or chart sizes intended for production. In general, these are of the order of 48 inches by 72 inch sheet sizes with image sizes only slightly less than the maximum sheet size. The question of EBR applicability to the production of such large separations hinges on the questions of product tolerance. We have proposed that the master (color separation negative and/or pressplate) have dimensional fidelity of one mil. For products of this accuracy requirement, the roughly 24,000 x 36,000 data points in the total graphic image format would not allow for the

use of a single EBR frame to produce the entire color separation. Such separations will also doubtlessly impose virtually impossible optical performance requirements upon any projection system considered. In order to produce large color separations with two mil accuracy and resolution, using an EBR, it would appear to be required to break the data files up into portions which are sized to the resolving power of the EBR and subsequently create the pressplates through two to four step-and-repeat exposures. This type of step-and-repeat expose with the requirements for line merging is clearly a relaxation of the technology developed to allow the use of CRT printhead systems.

2.4.2 AUTOMATED AIR INFORMATION PRODUCTS SYSTEM

The Air Information Department (AID) is a production department forming an element of DMAAC. AID faces a relatively awesome task of the production and updating of a large number of graphic products used for worldwide aeronautical navigation. These products have a wide mix and include the following major items:

1. Planning documents,
2. VFR and en route supplements,
3. Airplane and seaplane stations of the world (ASSOTW),

4. Arresting gear,
5. En route charts, and
6. Instrument and approach procedures (IAP's) - for termination and departure of airfields.

These products have a wide range of sizes with the instrument approach procedures being the smallest at five inches by eight inches and the en route charts being the largest at approximately twenty by fifty inches. One of the most formidable requirements imposed upon AID is the very rapid update of this critical information. Most of the documents require updates every fifty-six (56) days, while some require twenty-eight (28) day updates. The reaction time from input to AID of new information to the output of fully published updated documents is only some fourteen (14) days. Included in this relatively short period are: Analyst time to evaluate the updating information and preparation of a corrected graphic, the manual drafting of corrected masters, creation of photographic negatives, and finally, the imposition of multiple negatives into open frame negatives for pressplate creation. Certainly, this production area represents one of the most burdensome programs presently underway in the DMA.

At the present time, the DMA has issued a contract through the Rome Air Development Center (RADC) to Synectics Corporation to produce a pilot automated system to replace this burdensome manual operation. The system consists of a formidable array of data processing hardware and software, and will utilize an electron beam recorder as the computer output graphic terminal.

The products to be produced will utilize an EBR microform graphic and an optical projection system to produce a film sheet negative from which a pressplate will be made by an outside contractor. The products to be produced, the image size of the EBR microform graphic, and the blowback magnification which will be used are indicated in Table 2-3 . The accuracy and resolution requirements for this program are such that in this application the EBR will be introduced into a production environment at performance requirements well within its capabilities. This is completely in context with the previously discussed (paragraph 2.1.6) derating of the performance parameters for a practical machine in a production environment as compared to the theoretical limits of performance.

2.4.3 MANAGEMENT GRAPHICS

Management graphics are a DMATC product which consist of:

1. Assessment graphics,
2. Requirement graphics,
3. Command requirement graphics, and
4. Catalog graphics.

TABLE 2-3

AAIPS PRODUCTS

Product	EBR Image Size (inches)	Blow-back Magnification
Planning Document	4.0 x 6.0	2X
VFR & En Route Supplement	3.75 x 8.25	1.33X
ASSOTW	4.0 x 6.50	2X
Arresting Gear	4.0 x 5.25	2X
En Route Charts	3.33 x 7.50	6X
IAP's	5.0 x 8.0	1X

In general, these products are a large scale rendition of a projection of either the entire world or one of twenty regional portions of the world. Both are produced on JOG size sheets (22-1/2" by 29") with the full world depiction done at 35 million to 1 scale, or regional scales of 7 million to 1. Overlayed upon the depiction of the land and ocean masses, is a relatively fine grid. This grid is used to depict,through various color coding or annotation schemes, information which is basically "demographic" in nature. The production of these graphics is highly repetitious and the proofing operations are quite expensive. At the present time, proofing may be as complex as a proof press run of some 100 copies, followed by distribution to field centers for accuracy verification.

It would appear feasible to utilize the EBR for the rather repetitive preparation of the base charts and for the imposition of the existing digital data base to depict the demographic type information. Furthermore, consideration has been given to the direct utility of microform graphics at the EBR output scale. In this case, the press proof run would consist of contact exposure duplication of the EBR graphic (all color separations combined) and the transmission to proofing sites of a small graphic. Obviously, the proofing operation would require the use of an optical viewer such as a standard microfiche viewer. The accuracy, resolution, and scale of these products suggest that the microform graphic could easily be done in standard microfiche format and the proofing could be done using a microfiche reader which would resolve a number of contiguous grid segments.

2.4.4 EBR PROJECTION PRODUCTS

EBR output can be configured to be useful for projection graphics such as used in command and control briefing situations and in radar land mass simulations. In both applications, the utilization of 35 mm film would appear to be the appropriate recording medium for standard projection systems.

The use of EBR graphics for such projection applications can simplify the display systems when compared with a digitally driven soft display utilizing a high resolution CRT. In addition, the wide dynamic range of the EBR can be exploited in an optical projection system which does not encounter the gray scale limitations of a cathode ray tube display system.

2.5 OTHER APPLICATIONS

The utility of the EBR technology has been assessed for applications that are outside of the production of cartographic output in the strict sense, but which have applicability to any production environment in which vast amounts of data must be manipulated and in which continuous tone information (photographic imagery) are utilized.

2.5.1 DATA BASE RECORDER

The EBR is certainly applicable to computer output microform data generation. It can be operated within the context of microfiche output in which case, the already developed and available to industry array of film handling and peripheral equipments are applicable.

At each of its production centers, the DMA is storing data bases that are truly formidable in size. At the Topographic Center for instance, there are presently in storage some three million color separation negatives. The information of that number of color separation negatives can easily represent a total stored data base of some 10^{15} bits. As time progresses, the data base is certainly not going to contract, and will probably have substantial pressures for expansion. The facility requirements for the recording, search and retrieval for such a large data base is a substantial undertaking. It is presently accomplished in relatively "brute force" fashion by physically large filing systems. In the near term, one can see the conversion of this

data base to a strictly digital form in which case voluminous amounts of magnetic tape storage would be required.

EBR microform graphics can be used as a highly efficient analog storage medium for archival data. The technology is also applicable to direct digital recording in which the very high packing density, which is achievable through the combination of the high resolution electron beam and the fine grained electron sensitive film, is utilized.

In either case, the utilization of the EBR as an archival data recorder must address the question of information retrieval. Figure 2-10 illustrates a design concept which would allow for the adaptation of the EBR as a scanning device in addition to its recording function. In the figure, a second electron focal plane is illustrated in between the electron source and the nominal film plane. This focal plane is extremely close to the nominal film plane, and is equipped with a high resolution phosphor. With the appropriate adjustment in focus field strength, the electron beam would be scanned in either raster fashion or following a data block pattern over the phosphor creating a light spot which would be of constant intensity subsequently modulated by the density in the previously exposed and processed film. The light transmitted through the photographic film would be collected and detected by a electronic detector spectrally matched to the output of the phosphor.

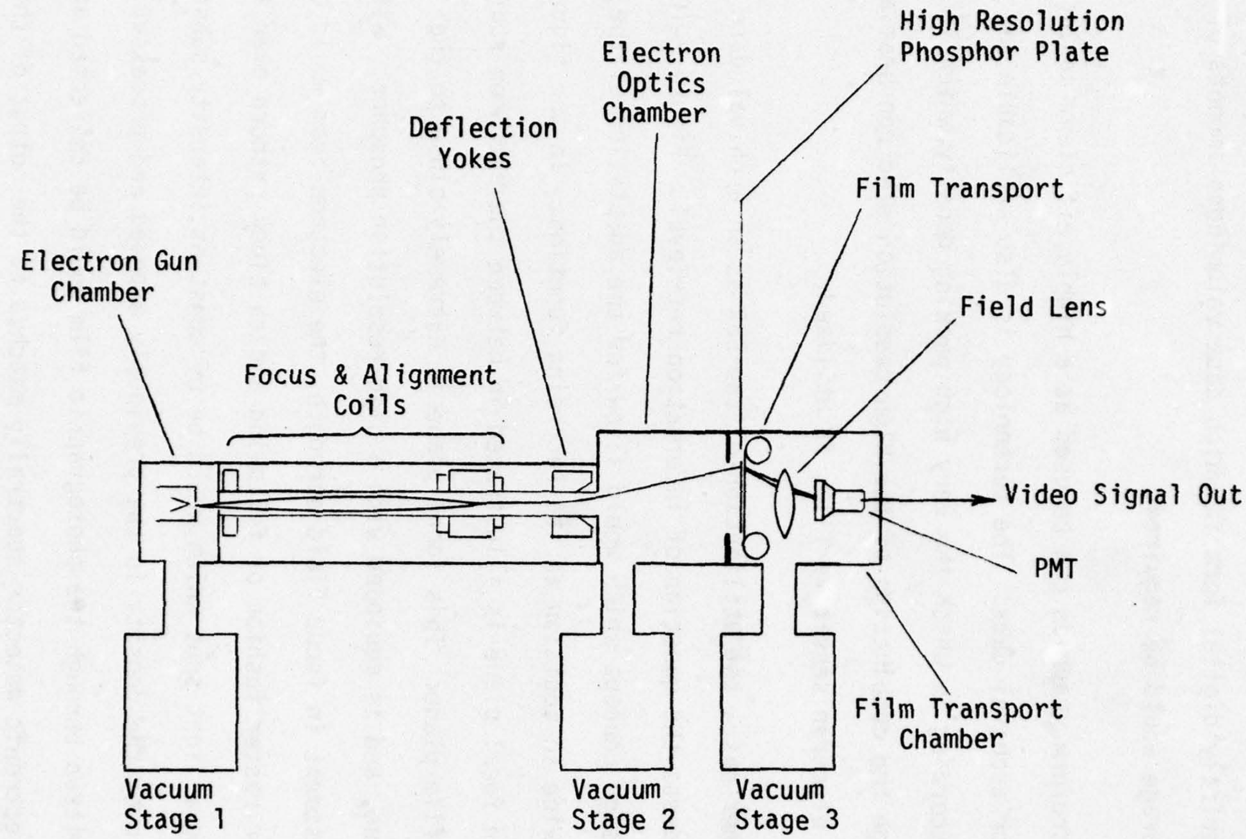

FIGURE 2-10

CONCEPT FOR USE OF EBR AS A SCANNING DEVICE

A variation on this process has been produced by RADC and Ampex Corporation in which the function of the separate phosphor is provided by a scintillation layer in the film emulsion. This is also a viable technique, but requires very substantial beam current to excite the scintillation layer. Normally, the beam current requirements are such that EBR filament life of considerably less than 1,000 hours is encountered. As a consequence of the short filament life, this is not the recommended technique for EBR readout.

2.5.2 CONTINUOUS TONE PRODUCTS

As discussed in Section I, many of the initial applications of EBR technology were found in the recording of satellite imagery. Figure 2-11 shows the transfer characteristics from a video signal to an output of an EBR. As seen in the figure, tonal control is available from a D_{min} (base plus fog) of 0.1 to a D_{max} of the order of 2.1 to 2.4. Beam intensity can be controlled in either a linear or logarithmic fashion which can, produce "gamma correction" to yield output imagery which is either linearly or logarithmically proportional to exposure.

In general, the artifacts normally associated with mechanical scanning are substantially reduced in a high resolution EBR. Normally, the EBR has resolution superior (in terms of number of TV lines per frame) to the sensor whose output it is recording. In such cases, the EBR is normally used in a "spot wobble mode" in which the characteristic artifacts of line scanning are virtually obliterated. In the image recording mode, the excellent dc restoration characteristics of the EBR can be maintained

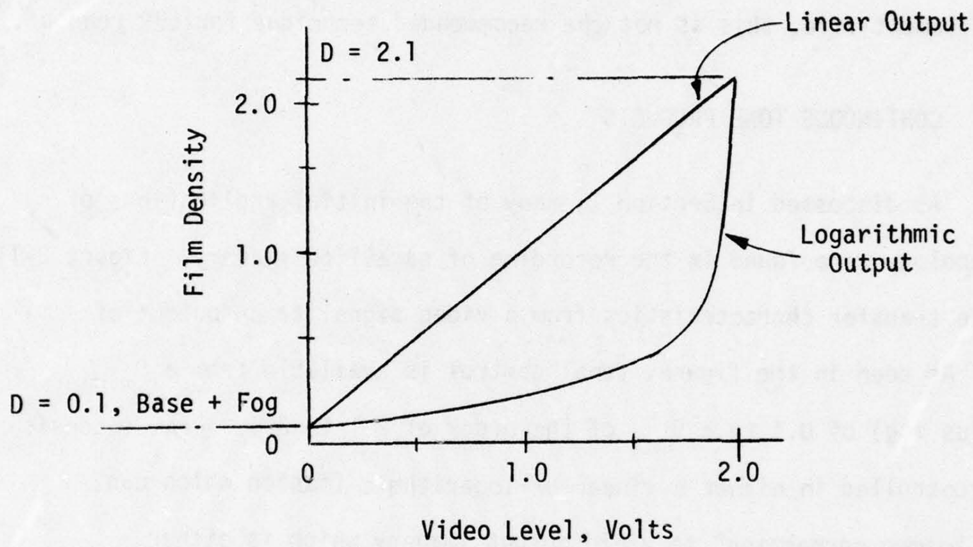

FIGURE 2-11

EBR SIGNAL TRANSFER CHARACTERISTIC

by sampling beam current on a once per line basis just outside of the format of the raster scan. This enhances overall tonal control and gives an absolute "black reference".

For applications in which the sensitometric performance of the EBR and recording film are important for subsequent analysis, well controlled sensitometric test wedges can be imposed on leaders and trailers of EBR film to ensure that photoprocessing variables, which may occur after EBR recording, can be adequately interpreted.

2.6 ECONOMIC CONSIDERATIONS

In the generation of pressplates, the costs associated with large sheet film are very significant. Film cost today is of the order of $0.70 per square foot to the large user. It is anticipated that the continued developments in "projection speed" plates will result in an even cost trade-off with wipe-on diazo in the near future.

The product cost of large sheet film, however, is only a portion of the economic story. Film pre-exposure storage, conditioning, handling, processing facilities, and post-exposure storage all represent significant factors that enter into the operating and facility costs of a printing operation. Among the special requirements pertinent to film storage are:

- light-tight environment (pre-exposure processing),
- controlled temperature and humidity,
- cutting flat form sheets from large rools in the dark environment, and
- flat form storage both pre and post exposure.

Projection platemaking has substantial economic merit compared to manual imposition and contact exposure at full plate scale. A high quality projection system can cost from $20,000 to $100,000 depending on the optical performance characteristics and system level complexity; "all-up" projection pagination systems can range from $200,000 to $400,000 when computer controls and precise step-and-repeat drives are included. To make the statement, then, that projection platemaking has economic merit, we must be able to demonstrate a cost savings that results in a "pay-back" of the capital investment of the projection platemaker in a period that is substantially shorter than the life of the platemaker (whether life is limited by wear-out or technological change).

Consider, for a quantitative example, the projection from a graphic or 5-1/2 inch roll film of a plate with 2 up imposition of JOG size sheets. Using an optical magnification of only 3.5, the film savings alone are a factor of 24.5 due to the use of the microform image. This material savings is approximately $4.75 per 2 up plate, or an annual savings of nearly $10,000 on the basis of an estimated 2,000 such plates being produced per year. The savings in facilities and space for the preparation and storage of plate sized negatives are not accurately known, but they add substantially to the $10,000 savings.

On the basis of the above highly simplified cost consideration, it can be seen that the 2 up imposition of JOG size charts can readily offer a 2 year pay back for the projection platemaker which for the modest 3.5X magnification required will be at the lower cost boundary for such equipment (approximately $20 to $25K).

The utility of 35 mm microfilm with a commercial projection/pagination platemaker such as the UMF Signamatic or the Pagination device will be found in production centers with high throughput of small "book-like" products. The Air Information Department of DMAAC is a prime candidate for an in-depth analysis to consider the trade-offs of the substantial amounts of contract labor presently expended in FLIP production compared to the capital expense of a 35 mm EBR microfilm recorder and a projector/paginator.

SECTION III

DISCUSSION AND CONCLUSIONS

3.0 GENERAL

This section discusses the major technical issues analyzed in Section II and draws conclusions as to the most promising methods for future exploitation of electron beam recorder technology in the context of the DMA's mission.

3.1 ELECTRON BEAM RECORDER PERFORMANCE

While great strides have been made in the growth of electron optical display and recording devices from 525 TV lines home television systems to present day electron beam recorders offering high quality performance at resolutions in excess of 10,000 TV lines per raster height, it appears likely that graphic arts quality performance in enlarged images should be limited to the range of 10,000 to 16,000 TV lines per raster height for the foreseeable future. Note that this does not suggest that EBRs with <u>limiting</u> resolution of 10,000 to 16,000 TV lines should be specified. In fact, for acceptable edge acutance and especially for high resolution performance in continuous tone images, an MTF at the performance point required (the 10,000 to 16,000 TV line frequency) should be specified to be approximately 50%. This means that limiting resolution will be in the region of 25,000 to 40,000 TV lines per raster height.

The testing of electron beam recorder systems should be done in both "stand alone" fashion in which the EBR is driven by internal test pattern generators, and in a subsystem context in which the efficacy of the transfer of digital data records and instructions are evaluated.

In the internal calibration mode, it is important that machine performance be evaluated in both the in-scan (horizontal) and cross-scan (vertical) directions. To this end, calibration patterns which produce rulings in both directions are required. These bi-directional patterns will assure that the beam spot is appropriately aligned and is free from astigmatism. They will also account for MTF loss due to sampling.

In subsystem tests, digital data records of comprehensive graphics such as the cartographic test standard are of great use in the process of determining the capability of the software/hardware system to cope with the artifacts of difficult graphical plotting procedures. Such patterns as concentric circles and vector "star bursts" have been particularly useful in understanding the artifacts of data transformations and recording device performance.

3.2 PLATEMAKING FROM MICROFORM IMAGES

From a subjective standpoint, there are several projection systems available which are useful for the projection of EBR microform images onto large sheet film and sensitive pressplate materials. In most cases, however, these projection systems have been developed for the graphic arts industry. Subjective evaluation of the quality is generally sufficient for this industry's evaluation of suitable products for their needs. In order to relate the technical performance capabilities of such projection systems, it will be necessary to perform more quantitative engineering tests with specific candidate projection systems. Two systems that come to mind in this regard are the HLC projection system presently installed at USAETL and the Opti-Copy line. Conventional tribar test patterns could be projected at various magnifications to establish the MTF vs. spatial frequency for these projectors with magnification as a family parameter. Geometric fidelity tests are also of great importance and can be accomplished by projecting arrays of geometric patterns in which the departures from perfect geometry are readily measured. Such examples include square grids in which the differences in diagonals can be measured to determine departure from absolute squares, and circles in which elipticity can be determined.

In terms of spectral response and sensitivity of candidate pressplate materials, it seems that at the present time, the publishing industry is under adequate pressure to spontaneously develop materials of significantly greater sensitivity and more panchromatic response than the present day wipe-on diazo plates. For this reason, the authors have concluded that the DMA's interests will best be served by maintaining close contact with developers of these new and more sensitive materials. Continued mismatches of industry production size standards and DMA product requirements are expected to continue. It may be warranted, however, for the DMA centers to introspectively assess what impact on product utility would be derived from standardizing their maximum size products to industry wide maximum roll widths.

In the case of DMA products which are not charts or maps; namely those products previously referred to as "book like" in nature, serious consideration should be given to the development of a 35 mm EBR to be used for both electronic typesetting and graphic generation. This type of system, in concert with either a Pagination or UMF platemaking system, could dramatically increase product throughput for the quick response rapidly updated products mentioned in Section 2.4. The utility of 35 mm EBR output is dramatically enhanced by the spontaneous development by industry of microfilm projection systems for this specific use.

During discussions between the authors and several technical representatives of the DMA production centers, considerable questions were raised concerning the utility of EBR microform images as an intermediate image carrier. Certainly, if the program to develop a direct pressplate recording system, which will utilize as its input a digital data record results in useful reliable pressplate recording system hardware, the EBR microform utility may well be questioned. It can be argued that the requirement for a high resolution scanner to retrieve what previously existed as a digital data record is an unwarranted and unnecessary step in the press-platemaking process.

As previously stated, the utility of the EBR microform graphic is only assured if high quality projection systems are available. If such is the case, the utility question will fall into the area of speed of production and throughput requirements. The EBR technology is capable of recording graphic images at rates greater than digital information can presently be transferred and used to control the electron beam recorder. Such will most likely not be the case for laser platemakers. It is highly unlikely that a laser platemaker will be able to produce a full size pressplate in anything less than 30 minutes. The EBR, on the other hand, can expose a full frame of graphic data in tens of seconds. Even accounting for film processing time, the combination of EBR exposure, photoprocessing, and subsequent projection platemaking will have a far higher rate of throughput than a direct laser platemaker. In addition, if one considers the availability of such high

quality projection systems, the EBR microform images can be used to perform a proofing operation. It appears feasible to superimpose EBR graphics to create a projection proofing system. This is a product area in which further investigations should be considered. Finally, the previously mentioned vast difference in EBR microform packing density when compared with the volume of magnetic tape digital data records may at some time in the future, if not already, be an important consideration.

3.3 SPECIFIC PRODUCT STUDIES

One of the major impacts of studying the wide variety of DMA products has been the raising of the concept of separating those vast number of products which are large charts from the more routine booklet publication in terms of master recording technologies to be applied to each production problem.

Because it is an active program with technology applications relevant to this study program, scrutiny has been afforded the Automated Air Information Production System (AAIPS) which is underway at the Defense Mapping Agency Aeronautical Center. In this program, we find an example of the above mentioned concept. Of the six primary products to be produced

by this system, five are relatively small, and their image size areas range over a relatively small set of values. Only the en route charts depart from this size range. At the full size product scale, the product image area diagonal ranges from 9.43 inches for the flip chart instrument approach procedures to 14.4 inches for the planning documents. The average product image area diagonal of these five products is 12.9 inches. This compares with a diagonal of the image area of an en route chart of 49.2 inches or some 4 times greater than that of the average of all of the other products.

This large difference between product sizes places substantial cost-related design impacts on the cartographic output device intended to fulfill the requirements of each of these six products. As previously discussed, a 35 mm electron beam recorder using commerical pagination equipment would easily handle the five smaller products in this group. The above considerations suggest that it would appear appropriate to reassess the overall program requirements in the light of this examination of EBR and peripheral equipment requirements.

SECTION IV

RECOMMENDATIONS

4.0 GENERAL

As a result of the technical issues raised during the conduct of the study and the many discussions with DMA representatives at Headquarters and at the three production centers, the following recommendations are offered for DMA consideration. These recommendations follow the conclusions discussed in the previous section concerning the profitable areas for exploitation of EBR technology in the Defense Mapping Agency.

4.1 ELECTRON BEAM RECORDERS

A program of continued experimentation with the cartographic electron beam recorder at ETL, Ft. Belvoir, is recommended. Technical issues that should be pursued in this experimental program include further assessment of the total resolution and accuracy characteristics which should be sought from EBR technology especially in the light of the capabilities of optical projection systems (see 4.2 below).

In order to assess performance at resolutions in excess of the 10,000 to 16,000 TV lines per raster height performance capabilities considered routinely feasible by the authors, the wherewithal for generation of a test pattern in which the advertised maximum resolution of 32,768 by 20,480 picture elements in an 8" by 5" format should be generated.

In the soon-to-be-accomplished final acceptance testing of the cartographic EBR, additions should be made to the test plan. In particular, geometric fidelity should be studied by the examination of equality of diagonals in square grid patterns rathern than by relying on overlays which demonstrate the congruity of the machine, but do not assess true geometric fidelity.

In addition, the internal test patterns should be modified or software instructions should be generated to add to the testing patterns lines perpendicular to the presently existing cross-scan lines (which are always easier to resolve than in-scan lines). In this way, the effect of the sampling MTF will be discerned.

It is further recommended that careful assessment of the edge gradient produced by the combination of the six micron beam spot and SO-219 film be studied. It should be noted that analytically, the combination of a 6 micrometer gaussian beam spot and the characteristics (MTF and D log E) of SO-219 film do not yield a 1.0 density unit per micrometer edge gradient as specified for the cartographic EBR.

4.2 PLATEMAKING

DMA is currently keeping abreast of many developments in new materials for platemaking. It is recommended that this involvement continue and, in some areas, be enhanced through experimental evaluation of some of the most promising new materials. In particular, the K-C film developments applied to the graphic arts industry appear to be most promising. It is recommended that further experimentation with K-C films be implemented and that the electron sensitivity of K-C film be determined. Of particular interest for EBR technology exploitation would be the examination of the capabilities of an electron beam recorder to produce the pre-exposure charging of the K-C film. This might be done with either a defocused recording spot or with an auxiliary source of flood beam electrons.

As the primary question of EBR utility in the production of large scale graphics hinges on the quality of projection enlargement systems, it is recommended that state of the art graphic arts quality projection systems be subjected to experimental evaluation. A relatively simple measurement program is envisioned and it is recommended that both the HRC and the Opti-Copy systems be evaluated for resolving power and geometric fidelity.

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ELECTRON BEAM RECORDER APPLICATIONS STUDY.(U)
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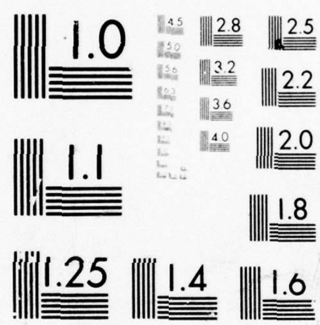


MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

4.3 SPECIFIC PRODUCT APPLICATIONS

In order to produce large size color separations, it has been determined that a step and repeat type of imposition projection will be required. It is recommended that the step and repeat accuracies of available imposition systems be evaluated in the context of the requirements for line and text merging of large charts.

For the production of JOG size charts, it is anticipated that the optical projection quality of either the Opti-Copy or the HRC projector combined with the already demonstrated capabilities of the cartographic EBR will suffice for the production of JOG size charts.

The AAIPS program, currently in the acquisition phase for a prototype system, has been studied in reasonable detail. It is recommended, as a result of this study, that the substantial size differences in the AID products be re-examined with the possibility of producing a 35 mm EBR which can use economically available step and repeat pagination projection systems for all of the small products. A larger format EBR or an alternate technology should be investigated for the en route charts.

Management graphics currently exist in digital data files at the Topographic Center. It appears that a relatively straightforward evaluation program can be conducted at ETL with some of the Topographic Center data files to determine the applicability of EBR technology to the production of management graphics. It is anticipated that this application will prove to be virtually an ideal use of EBR technology.

Projection products, as previously indicated, are most likely to have their greatest utility if they are formatted in consonance with existing projection systems. This clearly suggests the production of projection products such as radar land mass simulations and briefing material using the 35 mm format. Experimental evaluations can be made by using the 35 mm capability of the cartographic EBR at ETL.

The utility of the EBR as a mass data store can be evaluated both analytically and validated experimentally. It is anticipated that the high resolution, packing density, and good archival qualities of the electron beam sensitive films will demonstrate that EBR technology is indeed a viable candidate for a digital mass memory. Particular attention must be paid, however, to the methods of data address encoding for the retrieval portion of the information storage and retrieval mission.

The utility of the EBR for continuous tone imagery production has been well established for years. It is recommended that in EBR applications which are straight black and white or color separation graphics, that EBR complexity and cost be minimized by specifying only two density levels which would be widely separated. In programs in which continuous tone imagery will be a definite requirement, the wide dynamic range of the EBR can be specified to be between 128 and 256 shades of gray.

One final utility of EBR imagery appears to be projection proofing. It is recommended that further study and consideration be given to the utility of high quality rear screen projection for the proofing operation.

APPENDIX A

DEVELOPMENT OF MATHEMATICAL MODELS

OF

PROJECTION AND LASER SCANNER PLATEMAKING SYSTEMS

A.0 INTRODUCTION

In the discussion of the projection and laser scanner platemaking systems, mathematical models of these systems were presented. These models are derived in this appendix.

A.1 MODULATION TRANSFER FUNCTIONS

The modulation transfer function (MTF) describes the ability of the platemaking systems, or one of its components, to reproduce an input sine wave image. The MTF is defined as the amplitude response of the system. (It represents the amplitude term of the optical transfer function which also contains a phase term. In analyzing platemaking systems, only the amplitude term is important.) The overall system modulation transfer function, designated $\tau_s'(K')$, is the ratio of the modulation in the image (on the pressplate) to that in the object (on the microform) and is a function of the frequency of the input (or output) sine wave. This is,

$$\tau_s'(K') = \frac{M_i(K')}{M_o} \qquad \text{(A-1)}$$

$\tau_s'(K')$ = the MTF value for a sine wave of K' cycles/mm

K' = the spatial frequency referred to the pressplate

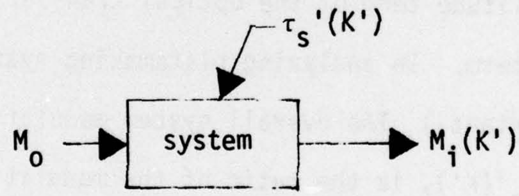
$M_i(K')$ = the modulation in the output image

M_o = the modulation in the object.

In certain cases, it is more meaningful to reference MTF's to the object (microform) plane. In such cases, the MTF value for a sine wave at K' cycles/mm at the pressplate equals the MTF value at K cycles/mm at the object plane, where

$$K = MK' \text{ (} M = \textit{linear magnification factor} \text{)}$$

A schematic representation of equation (A-1) would look like:



The object modulation, M_o, is defined for an object with a sinusoidal distribution of light as follows:

$$M_o = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \qquad \text{(A-2)}$$

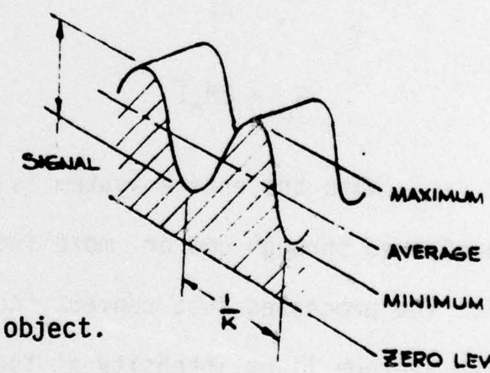
where

I_{max} = the maximum intensity of light from the object with sinewave distribution

I_{min} = the minimum density of light from the object

The object modulation can also be defined in terms of the contrast ratio of the scene by

$$M_o = \frac{C_R - 1}{C_R + 1} \qquad \text{(A-3)}$$



where

$$C_R = \frac{I_{max}}{I_{min}} \qquad \text{(A-4)}$$

and C_R = the contrast ratio of the object.

In the mathematical model for the platemaking systems, the signal is expressed in terms of the object modulation. The optical signal, S_o, is defined in all cases as the difference in extreme intensity levels.

$$S_o = \Delta I = I_{max} - I_{min} \tag{A-5}$$

In the same manner, if we assume that for all values of K, the average intensity, $\overline{I}$, is defined as:

$$\overline{I} = \frac{I_{max} + I_{min}}{2} \tag{A-6}$$

then equation (A-2) becomes

$$M_o = \frac{\Delta I}{2\overline{I}} \tag{A-7}$$

or

$$S_o = 2M_o\overline{I} \tag{A-8}$$

When the entire system is considered, the optical signal is transferred through one or more individual components, each having a unique MTF. The processes that convert the average light intensity of the object to an average light intensity at the pressplate also reduce the modulation of the object. The output signal, S(K'), of a platemaking system is therefore given by the equation:

$$S(K') = 2M_i(K')\overline{I}' \tag{A-9}$$

or

$$S(K') = 2M_o \tau_s'(K')\overline{I}' \qquad \text{(A-10)}$$

where $\overline{I}'$ is the average irradiance at the image (plate) plane.

Equation (A-10) has been used below in developing the signal expressions for the various platemaking systems.

The specific modulation transfer function that must be considered in modeling platemaking systems is the MTF associated with the projection optics. These optics take different forms depending upon the specific system. In addition, not only on-axis, but also off-axis performance (MTF) of the optics must be considered. The complexity of some projection optics, and the need to know their off-axis performance, makes development of an accurate mathematical model for this MTF very complicated. The preferred approach is rather to obtain measured MTF data from the manufacturer. In lieu of such data, a simplistic, on-axis, mathematical formula for the MTF of a diffraction limited lens is:

$$\tau(K) = \frac{2}{\pi}\left[\cos^{-1}(A) - A\sqrt{1-A^2}\,\right] \qquad \text{(A-11)}$$

where

$A = \frac{F\lambda K}{D}$

F = focal length of lens

λ = wavelength of light

K = spatial frequency at the object plane

D = lens diameter

A.2 DEVELOPMENT OF MATHEMATICAL MODEL FOR A NON-LASER PROJECTION SYSTEM

A qualitative description of a non-laser projection system is presented and shown schematically in Section 2.2.1.2 of the text.

The output power, P, of the high intensity source can be expressed in the form:

$$P = P_p \int_o^{\infty} P_\lambda d\lambda \quad \text{(watts)} \tag{A-12}$$

where

P_p is the peak monochromatic output power (watts)

P_λ is the relative output power.

For: a reflector collection efficiency, χ,

a reflector reflection coefficient, $R_r(\lambda)$,

a dichroic mirror reflection coefficient, $R_d(\lambda)$,

a filter transmission coefficient, $t_{ft}(\lambda)$,

and a beam shaping optics transmission coefficient, $t_b(\lambda)$,

the total power, P', reaching the film (object) plane is equal to:

$$P_p\chi \int_o^{\infty} R_r(\lambda)R_d(\lambda)t_{ft}(\lambda)t_b(\lambda)P_\lambda d\lambda \quad \text{(watts)} \tag{A-13}$$

This power is concentrated over an area, A, at the film plane. Thus, the power density, I, at the film plane is given by the equation:

$$I = \frac{P'}{A} = \frac{P_p \chi \int_0^\infty R_r(\lambda)R_d(\lambda)t_{ft}(\lambda)t_b(\lambda)P_\lambda d\lambda}{A} \quad (\text{watts/cm}^2) \quad \text{(A-14)}$$

As discussed in the text, a portion of this power is absorbed by the film. For a "base plus fog" film transmission coefficient, $t_f(\lambda)$, the maximum power transmitted through the film is equal to:

$$\frac{P_p \chi \int_0^\infty \ldots\ldots\ldots t_f(\lambda)d\lambda}{A} \quad (\text{watts/cm}^2) \quad \text{(A-15)}$$

To permit later use of equation (A-10), the average power transmitted is also important. If the assumption is made that "black" picture elements on the film transmit almost no light, then, the average power transmitted is approximately one-half of the maximum power. This light is projected through the use of projection optics onto the plate (image) plane.

For a projection optics transmission coefficient, $t_p(\lambda)$, a projection optics collection efficiency, C_p, and a linear magnification ratio, M, the average irradiance, $\overline{I}'$, at the plate plane is given by the equation:

$$\overline{I} = \frac{C_p P_p \chi \int_0^\infty R_r(\lambda)R_d(\lambda)t_{ft}(\lambda)t_b(\lambda)t_f(\lambda)t_p(\lambda)P_\lambda d\lambda}{2AM^2} \quad (\text{watts/cm}^2)$$

(A-16)

It should be noted that the projection optics collection efficiency, C_p, depends not only upon the projection optics, but also upon the nature of the light being transmitted through the film. If the light is "Lambertian" in nature, then

$$C_p = \frac{1}{4(f/\#)^2(M+1)^2} \tag{A-17}$$

where f/# is the f-number of the projection optics. If the light is more directional (specular), C_p will have a value greater than that calculated by this equation.

By substituting $\overline{I}'$ into equation (A-10), the signal, S, at the plate plane is given by the equation:

$$S(K') = \frac{M_o \tau_p' C_p P_p \chi \int_o^\infty R_r(\lambda) R_d(\lambda) t_{ft}(\lambda) t_b(\lambda) t_f(\lambda) t_p(\lambda) P_\lambda d\lambda}{AM^2}$$

$$(\text{watts/cm}^2) \tag{A-18}$$

A.3 DEVELOPMENT OF MATHEMATICAL MODEL FOR A LASER PROJECTION SYSTEM

A qualitative description of a laser projection system is presented and shown schematically in Section 2.2.1.3 of the text.

The output power, P, of the laser can be expressed in the form:

$$P = \sum_{i=1}^{n} P(\lambda_i) \quad \text{(watts)} \tag{A-19}$$

where

$P(\lambda_i)$ is the laser output power at wavelength λ_i, and

n is the number of output wavelengths associated with a particular laser.

For a beam shaping optics transmission coefficient $t_b(\lambda_i)$,
a galvanometer mirror reflection coefficient $R_g(\lambda_i)$, and
a lens transmission coefficient, t_{L1},

the total power, P', reaching the film plane is equal to:

$$\sum_{i=1}^{n} t_b(\lambda_i)R_g(\lambda_i)t_{L1}(\lambda_i)P\ (\lambda_i) \quad \text{(watts)} \tag{A-20}$$

If the area of the laser beam spot at the film plane is A, then the irradiance, I, at the film plane is given by the equation

$$I = \frac{\sum_{i=1}^{n} t_b(\lambda_i)R_g(\lambda_i)t_{L1}(\lambda_i)P(\lambda_i)}{A} \quad (\text{watts/cm}^2) \tag{A-21}$$

The subsequent development of this model parallels exactly that of the non-laser projection system. Thus, the average irradiance, $\overline{I}'$, at the plate plane is given by the expression:

$$\overline{I}' = \frac{C_p \sum_{i=1}^{n} t_b(\lambda_i)R_g(\lambda_i)t_{L1}(\lambda_i)t_f(\lambda_i)t_p(\lambda_i)P(\lambda_i)}{2AM^2} \tag{A-22}$$

$$(\text{watts/cm}^2)$$

Similarly, the signal, S, at the plate plane is given by the expression:

$$S(K') = \frac{M_o\tau_p{}'C_p \sum_{i=1}^{n} t_b(\lambda_i)R_g(\lambda_i)t_{L1}(\lambda_i)t_f(\lambda_i)t_p(\lambda_i)P(\lambda_i)}{AM^2} \tag{A-23}$$

$$(\text{watts/cm}^2)$$

A.4 DEVELOPMENT OF MATHEMATICAL MODEL FOR A LASER PLATEMAKER

A qualitative description of a laser platemaker is presented in Section 2.2.2 of the text and is shown schematically in Figure 2-8 . As discussed in the text, the scanning out of the microform image is accomplished in much the same way as it is done in the laser projection system. Consequently, the total power, P', reaching the film plane can be determined using equation (A-20). If, A_1, is the area of the "scanning out" laser spot (highly focused for this system), then the irradiance, I, at the film plane is P'/A, that is:

$$I = \frac{\sum_{i=1}^{n} t_b(\lambda_i)t_g(\lambda_i)t_{L1}(\lambda_i)P(\lambda_i)}{A_1} \quad (\text{watts/cm}^2) \qquad \text{(A-24)}$$

For a "base plus fog" film transmission coefficient, $t_f(\lambda_i)$, the <u>average</u> power transmitted through the film is

$$\frac{\sum_{i=1}^{n} t_b(\lambda_i)t_g(\lambda_i)t_{L1}(\lambda_i)t_f(\lambda_i)P(\lambda_i)}{2} \quad (\text{watts}) \qquad \text{(A-25)}$$

This light is collected by a "collecting" lens and imaged onto the face of a photomultiplier tube. The average current out of the photomultiplier can be determined by knowing the transmission coefficient, $t_c(\lambda_i)$, of the collecting lens, the sensitivity of the photocathode and the gain, G_m, of the multiplier.

If the photocathode sensitivity is given by the expression

$$S_p \sigma(\lambda_i)$$

where

S_p is the peak monochromatic photocathode sensitivity, and

$\sigma(\lambda_i)$ is the relative photocathode response,

then the average current out of the multiplier is given by the expression:

$$\frac{G_m Sp \sum_{i=1}^{n} t_b(\lambda_i) t_g(\lambda_i) t_{L1}(\lambda_i) t_f(\lambda_i) t_c(\lambda_i) \sigma(\lambda_i) P(\lambda_i)}{2} \quad \text{(amps)} \tag{A-26}$$

The signal, S(K), corresponding to this average current is given by the equation (referencing equation A-10):

$$S(K) = \tau_{L1} M_o G_m S_p \sum_{i=1}^{n} t_b(\lambda_i) t_g(\lambda_i) t_{L1}(\lambda_i) t_f(\lambda_i) t_c(\lambda_i) \sigma(\lambda_i) P(\lambda_i) \quad \text{(amps)} \tag{A-27}$$

Developing the model for the write-in portion of the system parallels that of the scanning-out portion described above. The light from the write laser is modulated by the video signal from the photomultiplier tube. The modulated light passes through the beam shaping optics, is reflected by the galvanometer mirror(s) and projected by way of the projection optics onto

the pressplate. The average irradiance, $\bar{I}'$, at the pressplate plane is, thus, given by the equation:

$$\bar{I}' = \frac{\sum_{i=1}^{n} t_m(\lambda_i)t_b(\lambda_i)t_g(\lambda_i)t_p(\lambda_i)P(\lambda_i)}{2A_2} \text{ (watts/cm}^2) \qquad \text{(A-28)}$$

where

$t_m(\lambda_i)$ is the transmission of the modulator in "on" mode,

$t_p(\lambda_i)$ is the transmission coefficient of the projection lens,

A_2 is the area of the "write-in" spot, and

$t_b(\lambda_i)$, $t_g(\lambda_i)$ and $P(\lambda_i)$ are defined above.

The signal, S(K'), corresponding to this average irradiance is given by the equation:

$$S(K') = \frac{\tau_p' \sum_{i=1}^{n} t_m(\lambda_i)t_b(\lambda_i)t_g(\lambda_i)t_p(\lambda_i)\ P(\lambda_i)}{A_2} \qquad \text{(A-29)}$$

$$\text{(watts/cm}^2)$$

Parameters Used in Analysis of UV and Visible Light Projection Systems

Collection efficiency of relfectors	75%
Reflection coefficient of reflectors	95%
Transmission coefficient of beam shaping optics	85%
Transmission coefficient of projection optics	80%
Collection efficiency of projection optics	50%

UV Projection System

Transmission coefficient of heat filter: Published data on Schott KG-1

Transmission coefficient of red absorbing filter: Published data on Schott BG-25 not Schott BG-37

Laser Projection System

Transmission coefficient of projection optics	80%
Collection efficiency of projection optics	95%

Laser Platemaking System

Transmission of modulator	50%
Transmission coefficient of beam shaping optics	80%
Transmission coefficient galvanometer mirror	95%
Transmission coefficient of projection optics	90%

EBR Film Parameters

Film transmission coefficient	0% (250 nm - 300 nm) 60% (300 nm - 350 nm) 85% (350 nm - 400 nm) 90% (400 nm and above)
Film specific heat	0.55 BTU/lb - °F
Film weight	3.5×10^{-2} lbs/ft^2
Film expansion coefficient	1.0×10^{-5} in/in - °F